N77-23628

JSC-11769

NASA TECHNICAL MEMORANDUM

NASA TM X 58199
February 1977

PROCEEDINGS OF THE SPACE SHUTTLE ENVIRONMENTAL ASSESSMENT WORKSHOP ON TROPOSPHERIC EFFECTS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058

1. Report No. NASA TM X-58199	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PROCEEDINGS OF THE SPACE SHUTTLE ENVIRONMENTAL ASSESSMENT WORKSHOP ON TROPOSPHERIC EFFECTS		5. Report Date February 1977
		6. Performing Organization Code JSC-11769
7. Author(s) Burton G. Cour-Palais, Compiler		8. Performing Organization Report No.
		10. Work Unit No. 383-85-00-00-72
9. Performing Organization Name and Address Lyndon B. Johnson Space Center Houston, Texas 77058		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This document is an account of the proceedings of the Space Shuttle Environmental Assessment Workshop on the tropospheric effects of Space Shuttle exhaust, held at the NASA Lyndon B. Johnson Space Center, Houston, Texas, on May 17 and 18, 1976.

Representatives of NASA centers and NASA support contractors provided working papers and/or presentations on various aspects of the environmental effect of Space Shuttle exhaust, sonic boom, and launch noise. The working papers and presentations were reviewed and discussed by panels formed from the participants. Results were reported by the panel chairmen and are provided in sections 1 to 10 of this report. A brief summary of the results is given first, followed by a detailed review of each topic. The position papers and presentations are included in the appendixes for completeness; however, they do not necessarily reflect the final positions adopted in the text of this report.

17. Key Words (Suggested by Author(s)) Weather modification; Air quality monitoring; Noise prediction; Environmental effects; Exhaust gas; Space Shuttle ~~effluents~~; Troposphere		18. Distribution Statement STAR Subject Category: 45 (Environment Pollution)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 209	22. Price* $7.75

*For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA — JSC

JSC Form 1424 (Rev Jul 74)

NASA TM X-58199

PROCEEDINGS OF THE SPACE SHUTTLE ENVIRONMENTAL ASSESSMENT WORKSHOP ON TROPOSPHERIC EFFECTS

Burton G. Cour-Palais, Compiler
Lyndon B. Johnson Space Center
Houston, Texas 77058

Preceding Page Blank

CONTENTS

Section		Page
1	SUMMARY	1-1
2	INTRODUCTION	2-1
3	SOURCE TERMS	3-1
4	CLOUD-CENTERED DIFFUSION	4-1
5	CLOUD TRAVEL	5-1
6	RAINOUT OR WASHOUT FROM THE STABILIZED GROUND CLOUD	6-1
7	INADVERTENT WEATHER MODIFICATION	7-1
8	SONIC BOOM	8-1
9	LAUNCH NOISE	9-1
10	EXPOSURE LIMIT GUIDELINES	10-1
APPENDIX A	— SOURCE TERMS	A-1
APPENDIX B	— CLOUD-CENTERED DIFFUSION ESTIMATES	B-1
APPENDIX C	— GROUND CLOUD MEASUREMENTS	C-1
APPENDIX D	— CLOUD TRAVEL	D-1
APPENDIX E	— ACIDIC RAINFALL	E-1
APPENDIX F	— SONIC BOOM AND LAUNCH NOISE	F-1
APPENDIX G	— MEDICAL AND BIOLOGICAL ALLOWABLES	G-1
APPENDIX H	— LAUNCH CLOUD NEUTRALIZATION FEASIBILITY STUDY	H-1

Preceding Page Blank

LIST OF PARTICIPANTS

PARTICIPANT	AFFILIATION
Paul Buchanan	NASA John F. Kennedy Space Center
James Perris	NASA John F. Kennedy Space Center
Hans W. Rudolph	NASA John F. Kennedy Space Center
Paul F. Wetzel	NASA Headquarters
L. Andrews	NASA Headquarters
Gary H. Minar	U.S. Air Force
Michael L. McCombs	U.S. Air Force
David L. Donley	U.S. Air Force
Darryl B . Dargitz	U.S. Air Force
John Miller	U.S. Air Force
Rafe Roig	U.S. Air Force
Richard L. Miller	U.S. Air Force
James R. Smith	The Aerospace Corporation
John S. Hickey	Science Applications, Inc.
Ray Rodrique	Tetra Tech., Inc.
Harrison E. Cramer	H. E. Cramer Company
Eric E. Rice	Battelle Columbus Laboratories
Rutherford C. Wooten, Jr.	U.S. Air Force
David C. Woods	NASA Langley Research Center
Gerald L. Pellett	NASA Langley Research Center
Gerald L. Gregory	NASA Langley Research Center
Paul F. Halloway	NASA Langley Research Center
Dick Hamilton	NASA Lyndon B. Johnson Space Center
J. Briscoe Stephens	NASA George C. Marshall Space Flight Center
D. S. Nachtwey	NASA Lyndon B. Johnson Space Center
Frank Garcia, Jr.	NASA Lyndon B. Johnson Space Center
Karen M. Morrison	NASA Lyndon B. Johnson Space Center
Robert D. Hudson	NASA Robert H. Goddard Space Flight Center
Ronald Dawbarn	ARO, Inc.
Arnold Goldford	Science Applications, Inc.
Rich Gomberg	NASA Langley Research Center
H. Scott Wagner	NASA Langley Research Center
C. C. Gay, Jr.	NASA Lyndon B. Johnson Space Center
Sidney Katz	Illinois Institute of Technology Research Institute
Curtis L. Ferrell	Illinois Institute of Technology Research Institute
Wilber R. Boykin	NASA Lyndon B. Johnson Space Center
John Q. Miller	NASA George C. Marshall Space Flight Center
Donald J. Kessler	NASA Lyndon B. Johnson Space Center
Burton G. Cour-Palais	NASA Lyndon B. Johnson Space Center
John Stanley	NASA Lyndon B. Johnson Space Center
Robert D. Rundel	NASA Lyndon B. Johnson Space Center

LIST OF PARTICIPANTS-Concluded

PARTICIPANTS	AFFILIATION
Donald L. Fenton	Illinois Institute of Technology Research Institute
G. G. Lala	Atmospheric Sciences Research Center
A. E. Weller	Battelle Columbus Laboratories
A. N. Dingle	University of Michigan
Owen R. Cote	U.S. Air Force
Richard K. Siler	NASA Lyndon B. Johnson Space Center

PANEL MEMBERS

I. Source Terms

Donald J. Kessler, Chairman
Dr. Richard I. Gomberg
Dr. Arnold I. Goldford
Dr. Eric E. Rice

II. Cloud-Centered Diffusion

Dr. Robert D. Hudson, Chairman
Dr. J. Briscoe Stephens
Dr. Owen R. Cote
Dr. Wilber R. Boykin
Dr. Gerald L. Gregory
David C. Woods

III. Rainout, Washout, and Inadvertent Weather Modification

Burton G. Cour-Palais, Chairman
Dr. Gerald L. Pellett
Dr. Robert D. Rundel
Dr. Ronald Dawbarn
Dr. Sidney Katz
Curtis L. Ferrell
Dr. Donald L. Fenton
Prof. A. N. Dingle
Dr. G. G. Lala

IV. Cloud Travel

Richard K. Siler, Chairman
Dr. Harrison E. Cramer
Lt. Col. David L. Donley
Lt. Col. Gary H. Minar
Dr. John S. Hickey
James R. Smith
Capt. Darryl B. Dargitz

V. Medical/Biological Consequences

Dr. D. S. Nachtwey, Chairman
Dr. Paul Buchanan
Maj. Richard L. Miller
Maj. Rutherford C. Wooten, Jr.
Maj. Michael L. McCombs
A. E. Weller
Dr. H. A. Kaplan

PANEL MEMBERS - Concluded

VI. Environmental Statement Revision and Policy

Dr. Andrew E. Potter, Chairman
Paul F. Wetzel
L. Andrews
H. Scott Wagner
John Stanley
Ray Rodrique
James Perris
John Miller

VII. Sonic Boom

Paul F. Halloway, Chairman
Dr. Frank Garcia, Jr.
Dr. Dick Hamilton
Karen M. Morrison

1. SUMMARY

Combustion of the solid propellant used for the Space Shuttle launch vehicle produces large amounts of aluminum oxide dust and hydrogen chloride and carbon monoxide gases. Afterburning and shock heating in the exhaust plume oxidize most of the carbon monoxide to carbon dioxide and a portion of the hydrogen chloride to free chlorine. Oxides of nitrogen are also produced in small quantities. These exhaust products in the troposphere could potentially lead to toxic gas and dust effects at the surface and in the air, to acidic rainfall, to weather modification, and to cumulative damage to the local ecology.

At the Space Shuttle Environmental Workshop on Tropospheric Effects, representatives of the various NASA centers and support contractors presented working papers assessing the effect of the Space Shuttle exhaust on the environment. Participants in the workshop reviewed and discussed the working papers and drew the following conclusions.

1. The constituents of the ground cloud with afterburning show that almost all the carbon monoxide has been converted to carbon dioxide. Titan measurements confirm this; hence, carbon monoxide is no longer a Shuttle problem.

2. Hydrogen chloride concentrations at surface levels are predicted to approach 4 p/m for up to 5 minutes in about 5 percent of the probable meteorological cases anticipated at the NASA John F. Kennedy Space Center based on 1969 soundings. This level occurs within 10 kilometers of the launch site and inside the controllable boundary at the Kennedy Space Center. It is significantly less than the allowable 4 p/m for 10 minutes with 8-p/m peak levels.

3. The model used to predict Shuttle launches predicts concentrations a factor of about 10 larger than will actually be observed, based on the Titan III measurement program.

4. High in-cloud concentrations of hydrogen chloride and particulates could pose a hazard to certain types of aircraft flying through them.

5. Cloud travel can be predicted in most instances fairly well at 1 or 2 hours before lift-off (T-1 or T-2), possibly from T-6 to T-8 hours, but not before T-12 hours. Weather regimes characterized by weak pressure gradients are the exception.

6. Acidic rainfall is a current area of environmental concern. A preliminary model predicts initial rain pH values (mixing cup average) of 1.0 or less within the boundary of the Kennedy Space Center and between 2.0 and 1.0 at 100 kilometers from the launch site. The preliminary model agreed reasonably

well with the results obtained from an acidic rain measured after the Titan III/Viking B launch. The values recorded indicated a p(Cl^-) of 1.5 or less in a 5-square-kilometer area about 4 kilometers from the launch pad.

7. Inadvertent weather modification is possible in some cases as long as 2 days after launch but mostly within a 500-square-kilometer area from the pad. No cumulative weather modification of any significance is likely to occur for 40 Shuttle launches a year.

8. The guidelines of the National Research Council-National Academy of Science Committee on Toxicology for allowable public exposure levels, under planned and unplanned conditions, for individual solid-rocket-motor toxic gases are the accepted standards at this time. Guidelines for solid-rocket-motor effluents that account for synergistic effects are not available.

9. The Environmental Protection Agency allowable standards for particulates and the International Civil Aviation Organization sonic boom effects criteria are acceptable and still valid. No Environmental Protection Agency noise standards have been officially recognized, although standards for L_{eq}, the equivalent A-weighted sound level, have been suggested.

10. A peak ascent sonic boom of 287.3 pascals (6.0 psf) for the Space Shuttle is predicted to occur at approximately 740 kilometers (40 nautical miles) from the launch pad and out to sea. The entry sonic boom for Orbiter on the first orbital flight test (OFT-1) mission shows a peak overpressure of 100.5 pascals (2.1 psf), and it is anticipated this will be typical for all planned Shuttle missions at Edwards Air Force Base and at the Kennedy Space Center.

11. A very preliminary launch noise assessment for Space Shuttle ascent shows a peak value of 110 decibels at 15 to 19 kilometers (8 to 10 nautical miles) uprange and crossrange and 37 kilometers (20 nautical miles) downrange.

2. INTRODUCTION

The Space Shuttle Environmental Workshop on Tropospheric Effects was planned as a major review of the ongoing environmental assessmental tasks to determine whether there had been any significant developments that could require a revision of the 1972 Environmental Statement for the Shuttle Program and the NASA John F. Kennedy Space Center (KSC) Institutional Environmental Statement, Amendment 1. In addition, the U.S. Air Force Candidate Environmental Statement for space transportation system (STS) operations at Vandenberg Air Force Base was in preparation and required up-to-date information on the work being done by NASA on Shuttle tropospheric effects.

The tropospheric workshop proved valuable in that it pinpointed a number of areas in which the significance had changed since the 1972 statement was written; it also served to identify new data gaps. This report of the results of the workshop is intended to provide a current assessment of the Space Shuttle environmental effects within the troposphere.

The workshop was divided into seven task areas. A presentation was made in each area, followed by panel discussions that led to assessments and recommendations. A synopsis of each assessment is given in this section, and the assessments and recommendations are reported in the following sections.

GROUND-CLOUD CONSTITUENTS

The primary constituents, by weight, of the rocket exhaust are calculated at the exit plane to be approximately 21-percent hydrogen chloride (HCl), 24-percent carbon monoxide (CO), 30-percent aluminum oxide (Al_2O_3), 9-percent water (H_2O), 9-percent nitrogen (N_2), and 3-percent carbon dioxide (CO_2). By continuing the reactions beyond the exit plane to about 1 kilometer downstream to allow for complete afterburning, the composition in the plume (and ground cloud) changes to approximately 19-percent HCl, 0.1-percent CO, 30-percent Al_2O_3, 29-percent H_2O, 42-percent CO_2, and 2-percent chlorine (Cl_2). The significant differences are the oxidation of CO to CO_2 and the formation of free Cl_2. In addition, a small percentage of oxide (NO_x) (approximately 1 percent) is shown to be formed in the process.

The effect of the deluge water used for the reduction of acoustic effects in the Orbiter payload bay on the plume composition was investigated by the NASA Langley Research Center (LaRC). By using a reasonable rate coefficient to vaporize this additional water, it is predicted that the CO will still afterburn to CO_2 but the amount of nitric oxide (NO) and Cl_2 produced will be significantly less.

Some concern was expressed during the workshop about the asbestos used in the solid rocket booster (SRB) as motor case insulation and as an insulator in the exhaust. The LaRC performed an analysis and concluded that the expected in-cloud concentrations would be about 1.2 to 1.5 times the standard, neglecting any destruction of the fibers in the SRB combustion process, but that the expected surface concentrations would be much lower. Because the melting temperature of asbestos (1973 to 2073 K (1700° to 1800° C)) is much lower than the chamber and plume temperatures of 2773 K (2500° C), the asbestos fibers will be converted into spherules and/or decomposed into silicon, which removes the hazard. The Thiokol Corporation (Utah) has shown that decomposition is the primary mode of conversion.

If a catastrophic failure on the launch pad should occur, a low-pressure burn will result in a different composition for the resulting continuous source plume. A Thiokol Corporation calculation gives the primary constituents by weight to be about 17-precent HCl, 25-percent CO, 29-percent Al_2O_3, 10-percent H_2O, 9-percent N_2, 3-percent CO_2, and 4-percent Cl_2.

CLOUD-CENTERED DIFFUSION

The NASA diffusion model being used to predict Shuttle concentrations of HCl and Al_2O_3 on the surface and in the air (2 meters above the ground) uses an analytic solution to the equations that describes the atmospheric diffusion of the stabilized ground cloud. It allows for the atmosphere to be divided into quasi-homogeneous layers and can accommodate discrete changes in atmospheric structure (e.g., the land/sea interface). The primary advantage of this model, which was developed by the NASA George C. Marshall Space Flight Center (MSFC), is that it can provide real-time, onsite air-quality and Earth-quality predictions of the concentration and dosage field resulting from a launch vehicle ground cloud. The primary disadvantage is that is cannot predict changes in flow fields due to the land/sea interface or terrain effects. As mentioned previously, it can handle these effects by discrete changes in input parameters. A further advantage of the NASA model in its current form, the rocket exhaust effluent diffusion (REED) description, is that data processing takes less than 10 minutes.

The other type of model in use today employs a numeric solution to the diffusion equation that results in flow fields. Thus, numeric models can deal with changes in atmospheric data during the life of the ground cloud. However, this degree of sophistication requires a grid of simultaneous atmospheric data on a scale much greater than for the analytic models and a data processing time of about 1 to 2 hours. The current NASA position is that the preliminary analyses of the air and surface quality resulting from Shuttle launches at KSC do not warrant a change to a numeric model. However, NASA is comparing the outputs from its diffusion model and from several numeric models with the data obtained in the Titan III measurement program. The intent is to determine whether the numeric models are more accurate and, if so, whether changing models is worth the cost and effort involved.

The NASA multilayer diffusion model (REED description) was used to assess Shuttle air and surface HCl and Al_2O_3 concentrations resulting from an assumed 40 launches in 1 year. In order to include typical meteorological regimes, the KSC-area atmospheric data for 1969 were used. It was assumed that a launch would occur at 7 p.m. on 40 Wednesdays, 7 p.m. being chosen because it represents a worst case (i.e., cloud transport toward the mainland). As a result of this analysis, it is estimated that the normal peak concentration of HCl from a Space Shuttle launch would be approximately 2 p/m. The peak value obtained with the 1969 data set was about 4 p/m, which occurred in approximately 5 percent of the cases. At no time did any of these values occur at distances greater than 10 kilometers from the launch pad (i.e., outside the KSC controlled population area). It must be emphasized that these figures are still preliminary. A similar assessment using the 1965 atmospheric data set for KSC is underway. In this set, the rawinsonde soundings were taken four times each day, and it is possible that a meteorological condition could be identified that gives worse concentration levels.

The corresponding cumulative surface loadings of HCl, assuming all 40 cloud tracks were coincident, is 7.6 g/m^2 of HCl per year at approximately 5 kilometers from the launch pad. In practice, the surface loading should be much less than 1 g/m^2 of HCl per year. These figures were obtained using the rocket exhaust constituents at the exit plane (i.e., without afterburning). The effect of using the latest constituent percentages, as reported in section 3, is not expected to be significant. In the case of Cl_2, which is increased by the afterburning to approximately 10 percent of the HCl concentration, the resultant peak value would probably not exceed 0.4 p/m 95 percent of the time. This is well below the 10-minute short-term public exposure limit (PEL) of 1 p/m for Cl_2.

The measurement program, conducted primarily during the Titan III launches at the Air Force Eastern Test Range (AFETR), monitored both ground-level and airborne effluents as well as the physical characteristics of the ground cloud (i.e., volume, stabilization altitude, crosswind growth, etc.). Effluent measurements were mainly for HCl and Al_2O_3, although CO, CO_2, NO, and NO_x were also measured. The purposes of these measurements were to develop a data base for assessing the models and the analytical techniques used and to confirm the composition and concentration of species in the stabilized ground cloud. The Titan III was used because it is the largest current NASA solid-rocket-motor (SRM) launch vehicle and because it has a composition similar to that of the Shuttle. It develops about one-third the thrust level.

The maximum HCl ground-level concentration during the Titan III launches was 1.3 p/m at approximately 5 kilometers from the launch pad. Maximum total particulate loadings at approximately 3- and 10-kilometer distances from the launch pad were 400 and 100 $\mu g/m^3$, respectively. The HCl values within the cloud were in the range of 2 to 6 p/m with one exceptional reading of 40 p/m. Corresponding particulate values were 120 to 1500 $\mu g/m^3$ with one exception of 2600 $\mu g/m^3$. The exceptional measurements were obtained during a night launch in December 1974, when a part of the ground cloud was trapped above a strong inversion layer and another part just below it. The sample was obtained from the upper cloud, which was prevented from diffusing by the inversion. Airborne measurements have also confirmed the low CO values within the cloud. The maximum value was always less than 5 p/m and typically less than 1 p/m, the detection limit of the instrument. It can also be shown that CO_2 concentrations in the cloud at stabilization are essentially near ambient levels (240 to 320 p/b). The maximum value recorded for NO_x in the cloud was 1400 p/b.

Summarizing the NASA position on the characteristics of the ground cloud at stabilization (i.e., the definition of the major inputs into the model), the overall characterization is well defined for postlaunch analysis. The plume afterburning calculations and laboratory-derived HCl partitioning calculations appear to be valid. Discrepancies in effluent ratios are considered minor at this time because of the overpredictive nature of the model. Both CO and CO_2 have been shown to have no significant effect on the environment. Preliminary results suggest that this latter statement is also true when the acoustic water damping for the Shuttle is considered. The level of credence in the description of the stabilized ground cloud implied in the preceding discussion is a necessary prerequisite for confidence in the ground-level air-quality predictions.

The analyses that were performed by LaRC comparing the measured ground-level values of HCl and Al_2O_3 from the Titan III launches and the predicted values, using the NASA diffusion model and launch-time meteorological data, showed that the model overpredicts ground concentrations by about an order of magnitude. For those cases in which the cloud stabilization altitude and cloud trajectory inputs agree reasonably well with the actual cloud behavior, the model appears to be accurate within a factor of 10 (on the high side) for maximum HCl concentration, HCl dosage, and Al_2O_3 dosage at a given site. Thus, the Shuttle concentrations and dosages calculated using the current NASA REED description given in this section should be considered as upper limits. Actual concentrations will probably be smaller by factors of 3 to 10.

GROUND-CLOUD TRACK FOR KSC LAUNCH

The movement of the Shuttle ground cloud is important under the following circumstances:

1. High concentrations of HCl moving over unacceptable areas

2. A Shuttle ground cloud moving under a precipitating cloud

3. Entrainment in an incipient precipitation system

It is important to determine before launch if (1) or (2) is likely to occur. A study of the forecasts for individual Titan launches suggests that the ability to do this is reasonably good except for those weather regimes characterized by weak pressure gradients. Forecast error in these cases is usually large. It is possible that forecasts for the weather regimes in question can be significantly improved if the general trend in weather forecasting continues and if an appropriate effort is made to better understand this particular forecast problem.

ACIDIC RAINFALL AND MODIFICATION

A simple idealized model has been developed by LaRC for low- to moderate-humidity levels and stable conditions in the troposphere. When used with the multilayer diffusion model developed by MSFC or with any other diffusion model, it provides acidic rainfall footprints whenever onset of rainfall is assumed. Estimates for the Shuttle-induced acidic rain pH values show values of 1.0 or less at 10 kilometers from the launch site, and between 1.0 and 2.5 at 100 kilometers. These potential-pH predictions are for dispersing but mass-conservative SRB clouds and apply to the initial rainfall before significant depletion of in-cloud HCl concentrations, by washout.

Acidic rainfall was measured scientifically for the first time during the Titan III-Viking B launch in September 1975. Preliminary estimates indicated $p(Cl^-)$ values of 1.5 and less in a 5-square-kilometer area centered approximately 4 kilometers from the launch site. Comparisons of $p(Cl^-)$ with available predictions of rain pH for those in Titan III SRM clouds suggest reasonable agreement for the close-to-launch-site case.

Chamber studies involving small SRM rocket firings were conducted to determine the total HCl washout coefficients and values for HCl gas. The results obtained were 50-percent lower than the accepted theoretical and laboratory values that were used for the Shuttle acidic rainfall predictions previously cited.

Further work is continuing to refine the acidic rainfall model by considering high humidity and unstable atmospheric conditions. It is planned to assess the model against airborne sampling measurements of Shuttle ground clouds and tracer seeding experiments.

The assessment of the potential for weather modification suggests that individual Shuttle ground clouds could modify the local weather for as long as 2 days after lift-off. The area affected is less than 500 square kilometers except for fogs, which could affect an area of approximately 10 000 square kilometers. However, no large-scale or long-range (up to 7 days) weather modification is expected. It was also concluded that the cumulative weather modification effect of 40 Shuttle launches was insignificant.

SONIC BOOM AND LAUNCH NOISE EFFECTS

The procedures used to predict sonic boom overpressures on the surface are based on the model developed for the Apollo Program and the results obtained for launch and entry during the Apollo 15, 16, and 17 missions. The model is postulated to be valid for the Shuttle ascent and Orbiter entry based on wind-tunnel tests. The maximum ascent overpressure predicted for the Shuttle vehicle is 287.2 pascals (6.0 psf) at approximately 74 kilometers (40 nautical miles) from the launch site. These ascent sonic booms occur over the ocean and are not expected to cause any problems, based on previous experience with manned and unmanned launch vehicles. Entry sonic booms have been analyzed for the first orbital flight test (OFT-1), and the footprint shows that the peak overpressure does not exceed 100.5 pascals (2.1 psf) and that the maximum overpressure experienced by any town in the vicinity of the groundtrack is between 38.3 and 47.8 pascals (0.8 and 1.0 psf). The peak value for entry for all Shuttle entry profiles is not expected to exceed 100.5 pascals (2.1 psf) primarily because of the change in the entry/terminal-area-energy-management (TAEM) interface from 22 860 meters (75 000 feet) and Mach 1.5 to 25 300 meters (83 000 feet) and Mach 2.5.

No estimate of overpressures caused by the SRB's or the external tank on entry is available at this time.

A very preliminary assessment of the Shuttle launch noise level shows 120 decibels within an approximately 9-kilometer (5 nautical mile) radius of the launch pad and 110 decibels at approximately 15 kilometers (8 nautical miles) uprange and crossrange and 37 kilometers (20 nautical miles) downrange.

EXPOSURE LIMIT STATUS

The guidelines suggested by the Committee on Toxicology of the National Academy of Sciences for toxic gases present in the Shuttle SRB exhaust cloud or associated with Shuttle operations are adequate for this environmental effects assessment. However, guidelines must be obtained for the synergistic effects of the SRM exhaust products.

The Environmental Protection Agency (EPA) national primary and secondary standards for particulates and the International Civil Aviation Organization (ICAO) sonic boom effects criteria are acceptable guidelines for this assessment. However, no EPA guidelines and regulations are available at this time.

No limits for acidic rainfall effects on soils, plants, and aquatic areas are available. However, NASA is pursuing baseline studies on the ecology of the KSC area so that cumulative long-range effects can be evaluated after the Shuttle is operating. It is possible that the guidelines in question will not be available until then.

3. SOURCE TERMS

CONCERNS

The toxic combustion products of the solid-rocket-motor (SRM) propellant, oxidizer, and entrained water and air that are calculated at the exit plane of the boosters may not be the same as those contained in the stabilized ground cloud. Afterburning in the plume and the addition of cooling water for acoustical damping are modifying influences. The concern is that the analyses be completed to equilibrium or near-equilibrium conditions so that the toxic by-products of combustion are more accurately represented in the ground cloud.

AFTERBURNING

The products of combustion from a rocket motor have been traditionally given at the exit plane of the rocket nozzle. However, some reactions continue to take place beyond this plane due mainly to the mixing of air with the high-temperature plume (afterburning). These reactions, in general, are to change carbon monoxide (CO) to carbon dioxide (CO_2) and to produce nitric oxide (NO). Some chlorine (Cl_2) is also formed.

The percentages of exhaust products from both the SRM and the main engine are summarized in table 3-I. These results are agreed on by both Richard Gomberg of the NASA Langley Research Center (LaRC) and Arnold Goldford of Science Applications, Inc. (SAI); however, only the LaRC results have been carried far enough to predict the amount of Cl_2 shown. The total mass of the compounds formed as a result of afterburning is increased as the result of oxygen and nitrogen combining in the plume to form CO_2, NO, and water (H_2O). This is reflected in table 3-I by the total mass 1 kilometer downstream being greater than 100 percent of the nozzle exit plane flow. The chemically unchanged nitrogen (N_2) and oxygen (O_2) air molecules are not included in the percentages of afterburned compounds shown. The Orbiter main engine percentages are from reference 3-1.

WATER USED FOR PAD ACOUSTIC DAMPING

During launch, water is planned to be used as a means of acoustically damping the lift-off noise. This will be accomplished by flowing water at the rate of 1500 m^3/min (400 000 gal/min) into the exhaust plume. Because one-fourth of the ground cloud results from the plume on or near the launch pad, this could result in a significant change in the chemical composition of the ground cloud. The effect of the water is to lower the temperature of the plume, thus reducing the amount of afterburning. The amount of this reduction is not a sensitive function of the rate coefficient used to vaporize water in the range 10^{-16} T to 10^{-20} T. Using a "reasonable" rate coefficient (10^{-16} T), Gomberg predicts that CO will still afterburn to CO_2 but the amount of NO and Cl_2 will be significantly less. Verification by visible photographs, infrared scanning radiometer measurements, and aircraft measurements is currently underway.

ASBESTOS

Approximately 9980 kilograms (22 000 pounds) of inert material is used in the booster, 30 percent of which is estimated to be asbestos. Thiokol Corporation (Utah) has shown that at the high temperatures of the exhaust plume, all this asbestos will decompose, mainly into silicon. An analysis performed by LaRC (appendix A), which assumed no destruction of the asbestos, shows that the in-cloud concentration may be 64 to 85 $\mu g/m^3$ and that the surface concentration is about 2 orders of magnitude lower. The in-cloud concentration would slightly exceed the Environmental Protection Agency (EPA) 8-hour standard but the surface concentration would be well below it. LaRC also concludes that the plume temperatures are high enough to decompose the asbestos.

PARTICULATES

In addition to the aluminum oxide (Al_2O_3) particles from the SRM exhaust, the ground cloud will contain a significant amount of debris, such as sand, carried up by the plume.

EMISSION AT VARIOUS ALTITUDES

The amount of each combustion product that is deposited at selected altitudes is given in table 3-II (ref. 3-2). This table is basically the work of Gomberg as presented at the conference, with later corrections for the engine mass flow and trajectory. The Orbiter main engine data are from reference 3-1.

CATASTROPHIC FAILURE

In the event of a catastrophic failure on the launch pad, a low-pressure burn would result, releasing certain compounds into the atmosphere. These compounds, as calculated by K. Wandless (Thiokol Corporation), are as follows.

Compound	Percent weight
Al_2O_3	28.5
CO	24.6
HCl	16.8
H_2O	10.0
N_2	8.7
Cl_2	3.6
CO_2	2.8
H_2	2.1
Other	2.9

SOURCE PANEL RECOMMENDATIONS FOR PROGRAM STATEMENT REVISION

1. Update existing table 1 in "Environmental Statement for the Space Shuttle Program, 1972."

2. Update existing table 2 in the 1972 Environmental Statement with table 3-I of this report.

3. Include a section as follows:

   In the event of a catastrophic failure on the launch pad, a low-pressure burn would result, releasing certain compounds into the atmosphere. These compounds are as follows.

Compound	Percent weight
Al_2O_3	28.5
CO	24.6
HCl	16.8
H_2O	10.0
N_2	8.7
Cl_2	3.6
CO_2	2.8
H_2	2.1
Other	2.9

4. Update existing table 5 in the 1972 Environmental Statement with table 3-II of this report.

5. Delete CO statements and calculations that do not include afterburning.

6. Include the statement that "A significant amount of the solids in the exhaust is debris, such as sand, carried up by the plume."

7. Include the statement that "At high temperatures, the asbestos used for insulation in the chamber will decompose."

8. Change all tables to be in metric units only.

REFERENCES

3-1. Nozzle Exit Exhaust Products From Space Shuttle Boost Vehicle (November 1973 Design). JPL TM 33-712, 1975.

3-2. Gomberg, Richard I.; and Stewart, Roger B.: A Computer Simulation of the Afterburning Processes Occurring Within Solid Rocket Motor Plumes in the Troposphere. NASA TN D-8303, 1976.

TABLE 3-I.- EXHAUST PRODUCTS

[Percent by weight of nozzle exit plane flow]

Product	Nozzle exit plane	1 km downstream[a]
SRM (total mass flow ≈ 9.4×10^6 g/sec)		
HCl	21.2	18.9
Cl_2	0	2.1
Cl	.3	.03
NO	0	1.3
NO_2	0	.02
CO	24.1	.07
CO_2	3.4	42.2
H_2	2.1	0
OH and H	.02	0
N_2	8.7	(b)
H_2O	9.3	28.6
Al_2O_3 (solid)	30.1	30.1
$AlCl_2$ (solid)	.02	.02
$FeCl_x$ (solid)	.97	.97
Total	100.21	124.31
Orbiter main engine (total mass flow ≈ 4.7×10^5 g/sec)		
H_2O	95.9	128
H_2	3.5	0
Ar, N_2, other	.6	.6
Total	100.0	128.6

[a]Includes "complete" afterburning. The total is greater than 100 percent because of the chemical addition of air to the flow to form H_2O, NO, and CO_2.

[b]Assumed to be part of air.

TABLE 3-II.- COMBUSTION PRODUCTS OF CONCERN EMITTED BY THE SPACE SHUTTLE VEHICLE — PARALLEL SRM BOOSTER AND ORBITER LOX/LH_2[a] ENGINE AT SELECTED ALTITUDES

Combustion products	Amount,[b] g/m, at -			
	0.23 km	6 km	10 km	15 km
HCl	38 656	3984	2840	2198
Cl_2	4 352	480	420	426
Cl	61	28	60	192
NO	2 690	214	56	11
NO_2	36	3	.8	.3
CO	141	34	50	75
CO_2	84 114	8744	6548	5410
Al_2O_3 (solid)	61 496	6410	4836	4036
H_2	.06	.004	.01	.01
H_2O (SRM's)	58 410	6110	4640	3918
O	.0006	.001	.01	.2
OH	.01	.004	.02	.2
H_2O (LOX/LH_2)	13 000	2100	1900	1600

[a]Liquid oxygen/liquid hydrogen.

[b]Includes afterburning, which is calculated to 1 km downstream. More than 99 percent of the plume is air, which is not shown.

4. CLOUD-CENTERED DIFFUSION

CONCERNS

During the normal launch of any rocket, a characteristic ground cloud is formed at the base of the launch platform that consists of the hot exhaust products from the motors and any debris that might be drawn into the cloud from the platform area. Because of its bouyancy, the cloud slowly rises to a stabilization altitude (which for the Space Shuttle will be a few thousand meters), at which time it has become diluted by mixing with the ambient air. The principle constituents of this cloud will be hydrogen chloride gas (HCl), aluminum oxide (Al_2O_3) particles, carbon monoxide (CO), carbon dioxide (CO_2), chlorine (Cl_2), and nitric oxide (NO), although measurements on Titan ground clouds and calculations indicate that the levels of CO and NO will be small.

Once the cloud has reached the stabilization altitude, it will grow in size because of diffusion and will move with the prevailing wind at that altitude. There are several concerns about the fate of this cloud:

1. How much HCl gas diffuses down to the ground? What are its concentrations and for how long; i.e., what is the dosage that would be detected at ground level?

2. What are the possibilities of acid rain from an overriding rain storm?

3. What is the nature of the Al_2O_3 particles? Could they cause weather modification?

The latter two points will be considered in other sections. In this section, predictive models for the first point are discussed, the verification procedures that were performed to test the NASA model are described, and predictions of the effects of the Space Shuttle launches are given.

MODEL

The NASA George C. Marshall Space Flight Center (MSFC) rocket exhaust effluent diffusion (REED) description is composed of three models: (1) a meteorlogical model, which models the atmospheric input parameters; (2) a cloud rise model, which couples the atmospheric kinematic and thermodynamic parameters with the rocket exhaust chemistry for the initial source description; and (3) a diffusion model, which couples the atmospheric kinematic parameters with the source description to analytically predict the dispersive transport of the rocket exhaust effluents.

The purpose of the REED description is to provide air-quality and earth-quality predictions to support Space Shuttle launch operations. This application imposes the following constraints to the REED description: the predictions of the concentrations must be protective and the predictions must be made in near real time to be relevant. This application with these constraints influenced the development of an operational REED description.

Meteorological Model

The meteorological model is fundamentally either a forecast or a rawinsonde sounding for the initial 6000 meters (20 000 feet) of the atmosphere. The required resolution is 300 meters (1000 feet) per level with a 30-meter (100 foot) resolution required at the significant level.

The specific parameters for air-quality predictions are wind velocity (speed, direction, and variance profiles), virtual temperature profile, pressure profile, and surface density. Empirical models are currently used to obtain the variance in the azimuthal and elevational direction (refs. 4-1 to 4.7). Because of sounding limitations, the meteorological model is basically Eulerian (point); however, some Lagrangian (spatial) information is obtainable using tetroonsonde measurements (ref. 4-8) and a mesoscale meteorological model (ref. 4-9). It is reasonable to assume that Langrangian models will be available to support Space Shuttle operations.

Exhaust Cloud Rise Model

The exhaust cloud rise model (refs. 4-10 to 4-13) describes the first 5 to 10 minutes of the transport of the rocket exhaust effluents in accord with the kinematic and thermodynamic properties of the atmosphere. This model in turn provides the source description for the diffusion model.

There are basically two techniques to determine the height of the exhaust cloud stabilization: the Briggs buoyancy technique (ref. 4-13) and numerical techniques (ref. 4-14). The current operational cloud rise model is a modified Briggs model (ref. 4-10) that gives a reasonably quick solution. A research numerical cloud rise model could be developed to improve this description if required. Using the Briggs model, the cloud geometry is obtained from a semi-empirical model, whereas, using the numerical model, the cloud geometry is obtained from the thermodynamic structure of the atmosphere.

Diffusion Model

The diffusion model (refs. 4-10 to 4-12) is a Gaussian diffusion model that uses the atmospheric kinematics in conjunction with the source description to afford aerospace air-quality or Earth-quality predictions. The following discussion on the evolution of diffusion modeling is included to illustrate both the development and the alternatives of the current model.

Evolution of diffusion modeling.- The current NASA multilayer diffusion model has evolved from A. Fick's diffusion theory in 1855 (ref. 4-15). In 1921, G. I. Taylor introduced the K (eddy diffusivity) Theory (ref. 4-16). In the 1920's, a fission occurred in the solutions for the diffusion equation. O. F. T. Roberts (ref. 4-17) obtained an analytical solution using a Gaussian distribution and L. F. Richardson (ref. 4-18) used a numeric solution to obtain an exact solution.

Analytic solution: The analytic solution for the diffusion equation was the only solution basically used until the late 1960's. The primary problem was to evaluate the diffusion coefficients. Based on O. G. Sutton's indirect approach to the turbulent diffusion coefficient in the thirties and forties (refs. 4-19 and 4-20), Cramer, Cramer et al., and Pasquill (refs. 4-21 to 4-23, respectively) developed a direct (measured) turbulence diffusion coefficient in the late fifties. Using the Prairie Grass Experiments, Pasquill generated a set of curves for the turbulence diffusion coefficients, whereas the Cramer coefficents were algorithms. The Cramer coefficients were incorporated into the NASA multilayer diffusion model in the late sixties and early seventies for rocket exhaust diffusion problems (ref. 4-12). This diffusion model allowed the atmosphere to be layered in quasi-homogeneous layers for discrete changes in atmospheric structure (e.g., the land/sea interface).

Numeric solution: After Richardson's initial success with a numeric solution for the diffusion equations, this technique lay dormant because of the complexity of the solution until large computers became available in the sixties. All current numeric diffusion models (refs. 4-24 to 4-35) are basically providing a flow field; some models (ref. 4-29) are looking primarily at the transport of effluents, and others (ref. 4-30) are looking at the mesoscale transport of air. Both groups of models are using the primitive equations (no assumptions), which require very large computers (500K to 800K case) and long running times (approximately 1 hour). To circumvent this, Lavoie (ref. 4-9) and others have developed specialized numeric models — climatological models — to reduce computer requirements by more than one-half. Much research is currently underway in this area.

Present diffusion model.- The diffusion model used in the REED description affords estimates of the effects of rocket exhaust effluents on air quality and Earth quality. Although this description is primarily designed for Eulerian data input, it can be used in a simple discrete change model to utilize Lagrangian information. The primary advantage of the currently used Gaussian diffusion model is that it can provide near-real-time onsite air-quality and Earth-quality predictions of the concentration and dosage field resulting from the launch effluent of an aerospace vehicle (refs. 4-36 to 4-38). The primary disadvantage of this Gaussian model is that it cannot predict changes in flow fields due to the land/sea interface or a terrain effect, which can potentially be done with a numeric model if adequate atmospheric information is available. It can, however, model them in discrete changes when they are known. To date, this does not appear to be a serious disadvantage with the Gaussian model. However, to adequately support a mesoscale numeric diffusion model so that its results would be significantly better than the Gaussian model, a large grid of rawinsonde sounding would be required.

In summary, the totally analytic REED description would have a data processing time of less than 10 minutes, whereas a totally numeric REED description would have a data processing time of about 1 to 2 hours. From the analytic REED description, only a Eulerian prediction is obtained, whereas the numeric REED description affords a Langrangian prediction. The number of simultaneous rawinsonde soundings required for the numeric description is much greater than those required for the analytic description.

The potential Space Shuttle operational scenario for air quality then could be real-time onsite support with the analytical REED description and remote backup support with the numerical REED description.

AIR-QUALITY AND EARTH-QUALITY PREDICTIONS

Assumptions

To assess the effects on air quality and Earth Quality for a year of normal Space Shuttle operation, an appropriate data set was selected. The soundings from the NASA John F. Kennedy Space Center (KSC) for 1969 were selected since this appeared to be a representative year containing all the typical meteorological regimes (ref. 4-39) for the area. The meteorological data are Eulerian (rawinsonde soundings only).

To simulate normal Space Shuttle operations, the 7 p.m. (00:00 GMT) sounding was selected for each Wednesday during the year. The selection of a specific day each week does not noticeably affect the analysis; however, the selection of the time of day is important. There were only two soundings made each day in 1969: one at 7 a.m. (12:00 GMT) and one at 7 p.m. (00:00 GMT). Because the evening soundings represented more cases in which the exhaust effluents would be transported on shore where the public would be affected, these soundings were selected for the preliminary analysis.

No Lagrangian information (tetroonsonde tracks) was available; therefore, the effects of the land/sea interfaces were neglected. To ensure worst-case results, the top of the surface transport layer was set to be twice the height of cloud stabilization.

Because these results were intended only as initial working predictions, the NASA REED description was used with the rocket exhaust constituents given in "The Space Shuttle Environmental Impact Statement, 1972," and the ground cloud technique was used in the diffusion model (refs. 4-10 and 4-11). However, it is intended that the effect of using the latest rocket exhaust constituents (with afterburning) on the Shuttle prediction will be assessed. The effect of this change is not expected to be significant.

Results

The results of the air-quality and surface-loading predictions are summarized in figures 4-1 and 4-2, respectively. Tables 4-I and 4-II give the typical concentration and dosages for two cases included in figure 4-1.

The Space Shuttle air predictions for HCl and Al_2O_3 are summarized in figure 4-1. The duration of the exposures to a detectable concentration of HCl is normally less than 10 minutes; hence, an accumulative buildup of HCl is not a creditable air-quality scenario. From this analysis, the normal peak concentrations of HCl from a Space Shuttle launch are estimated to be approximately 2 p/m.

The worst-case surface loading for HCl is presented in figure 4-2. This result was obtained using the atmospheric data that give the worst-case air-quality prediction. It also assumes that all the HCl coming in contact with the surface is absorbed, which means that these results are probably too high by a factor of 2. To obtain an annual worst-case Earth-quality prediction, the exhaust is assumed to have the same transit path for all 40 launches. If this were the case, then the maximum buildup would be 7.6 g/m^2 of HCl per year, occurring about 5 kilometers from the launch pad. In practice, the surface loading should be much less than 1 g/m^2 per year.

The abort results for a single-engine burn and conflagrations are given in tables 4-III to 4-VI. The atmospheric conditions that gave the maximum and minimum air-quality predictions were used for these burns to limit the problem.

Figure 4-3 shows the HCl isopleths for what is probably a normal afternoon Space Shuttle launch. The atmospheric data are from the launch of Viking A.

An additional air-quality analysis for CO, CO_2, CL_2, and NO_x is not necessary because of the amounts present in the rocket exhaust and current air-quality exposure recommendations; that is, the signature constituent for a Space Shuttle air-quality problem is HCl.

NASA LAUNCH VEHICLE MEASUREMENT PROGRAM

Since early in 1972, NASA has been conducting effluent monitoring programs (refs. 4-40 to 4-45) in conjunction with selected NASA and Air Force launches in Florida. The purpose of these monitoring programs is to develop a data base for assessing the models and analytical techniques (refs. 4-12, 4-36 to 4-38, and 4-46 to 4-49) used by NASA in determining the environmental effect of launch vehicles on ground-level air quality. The monitoring program has focused mainly on the Titan III launch vehicle, which is currently the largest NASA solid-rocket-motor (SRM) launch vehicle; however, one Scout and numerous

Delta vehicles have also been monitored. To date, some 18 to 20 launches have been monitored with varied degrees of measurement sophistication. The Titan III monitorings typically consisted of both ground-level and airborne effluent measurements as well as measurements of the physical characteristics (volume, stabilization altitude, crosswind growth, etc.) of the exhaust effluent cloud formed at launch. Effluent measurement systems are mainly for HCl and particulate (Al_2O_3) measurements, although CO, CO_2, NO, and NO_x are also measured. The monitoring program is continuing with measurements of ground-cloud concentrations from Titan III and Shuttle static test firings. It is planned to monitor Shuttle orbital flight tests to obtain the actual ground-cloud airborne and surface data.

Source Term Measurements

With the modeling or analytical description of any physical phenomenon, the modeling process must be initiated at some point. In the case of the diffusion model used for the determination of ground-level effluent concentrations, this initializing point is "ground-cloud stabilization"; i.e., that point in time (5 to 10 minutes after launch) when the cloud has essentially reached thermal equilibrium with the ambient environment. A large part of the monitoring program (airborne sampling and cloud physical measurements) has been directed at providing data to define the exhaust cloud at stabilization (diffusion model initiation).

Cloud rise and stabilization.- Visible photography and infrared imaging of the exhaust cloud from SRM ignition to exhaust cloud stabilization have been used to assess such model inputs as cloud stabilization altitude, shape, and volume. Figures 4-4 and 4-5 show some of these measurements for various Titan III launches. Cloud altitude and volume measurements at stabilization are accurate to about 10 and 30 percent, respectively, and can be used as model inputs. In addition, measurements of the type shown in figures 4-4 and 4-5 are currently being used to refine various analytical techniques for calculating cloud stabilization altitude and volume. To date, refinements in such parameters as heat content of cloud and surface-level temperature (ref. 4-37), parameters used in cloud rise calculation, have resulted in more accurate calculations of cloud stabilization altitude to the point that 10- to 30-percent agreement with measured data is not unreasonable. The current cloud rise calculations underestimate the cloud stabilization altitude, which results in conservatively high level effluent predictions.

Initial cloud composition.- To determine the composition of the exhaust cloud at stabilization (model input), one must consider the history of the exhaust effluents from nozzle exit to exhaust cloud stabilization. Some of the more important processes that must be considered in this transition period are effluent emission rates from SRM's, afterburning and chemical reaction, and ambient air entrainment (dilution). At stabilization, the exhaust cloud is at least 99-percent ambient air. Table 4-VII shows the results of 1976 plume afterburning (ref. 4-50) and chemical reaction calculations for Space Shuttle. The weight percentages given are the same as those in table 3-I on a 100-percent basis. As compared to the July 1972 environment statement, notable changes in weight percentages of HCl, Cl_2, CO, H_2O, CO_2, and NO are shown. The 1972 values did not take into account plume afterburning or chemical reaction. A major part of the airborne sampling program conducted during the Titan III launches has been directed at confirmation of the composition and concentration of species in the stabilized ground cloud. (Titan III sea level afterburning calculations are nearly identical to the 1976 Shuttle values in table 4-VII.) Airborne in-cloud measurements have confirmed the low CO values (maximum CO is always less than 5 p/m and typically less than 1 p/m, the detection limit of the airborne instrumentation), and it can easily be shown that CO_2 concentrations in the cloud at stabilization are essentially near ambient levels (320 to 240 p/m). Table 4-VIII lists the maximum concentrations measured in the cloud during each of six Titan III launches. The higher values measured in December 1974 are attributed to the existing meteorology at that launch. Figure 4-6 is a typical example of the concentration/time data obtained during airborne sampling passes and indicates that the particulates and gas species are similarly distributed in the cloud. (Note that the particulate and HCl concentrations of figure 4-6 have been normalized.) Figure 4-7 shows the decay of the maximum in-cloud concentrations as a function of time. The step increase in the HCl and Al_2O_3 data at 20 minutes after launch (December 1974) is attributed to meteorology and the repositioning of the aircraft during the sampling mission. Figure 4-8 is a plot of the ratio of the major effluents of interest (Al_2O_3 and HCl) to NO_x, a mass-conserved species in the cloud. These ratios are nearly constant for a given launch, thus indicating that at cloud stabilization and beyond the major chemical reactions between the effluent species have ceased, and that the Al_2O_3 particulates in the cloud are diffusing like a gas (model assumption). This compares well with the laboratory data and theoretical calculations (ref. 4-51) on partitioning of HCl in the cloud shown in figure 4-9, which indicates that by the time of cloud stabilization (5 to 10 minutes) the majority of HCl is stabilized in the gas phase. Comparison of the HCl/NO_x ratios from figure 4-8 with the calculated ratio from table 4-VII shows the calculated ratio to be approximately 10, whereas the measurements show a ratio ranging from 2 to 6. (Note that the data of table 4-VII must be converted to mol fractions and that the majority of NO_x measured is NO.) Although this is a reasonable agreement considering the processes involved, studies to account for this difference are continuing.

In summarizing the position of NASA on the characteristics of the exhaust cloud at stabilization (i.e., the definition of the major inputs into the model), the overall characterization is well defined for postlaunch analysis. The plume afterburning calculations and the laboratory-derived HCl partitioning calculations appear to be valid. The discrepancies in effluent ratios are thought to be minor at this time considering the overpredictive nature of the model and the extent of the environmental impact. Both CO and CO_2 have been shown to have no significant effect on the environment. (Preliminary results suggest that this applies also for cases where the acoustic water damping system is being considered for Shuttle.) In-cloud concentrations of the major species of interest (Al_2O_3, HCl, and NO_x) have been measured for a variety of meteorological conditions and now are available for further refinement of the source terms (model). Techniques are available for measuring such important model inputs as cloud stabilization altitude and time, and in many cases these parameters can be adequately predicted. As the existing quantity of in-cloud data is studied in more depth, further refinement of the source terms can be envisioned.

Surface-Level Effluent Measurements

In the preceding section, the emphasis was placed on developing some credence in the description of the exhaust cloud at stabilization because this description is used as input to the diffusion model. No matter how adequate or detailed the description of this source cloud, the main question of interest still concerns the reliability of the model predictions of ground-level air quality. This section will address this question and, in doing so, will focus attention on the December 1974 and May, August, and September 1975 Titan III launches monitored in Florida. These launches were selected because there was a complete monitoring and modeling program associated with each launch. Earlier launches, although providing some meaningful data, were monitored at less levels of effort and were designed as preliminary experiments for refinement of operational procedures and instrumentation before the four major monitoring efforts. In this section, the experimental measurements made at specific locations during the four launches will be compared directly to corresponding predicted values. The guidelines for the comparisons are listed as follows.

1. Comparisons will be for maximum HCl concentration, HCl dosage, and Al_2O_3 dosage at the specified sites. The Al_2O_3 maximum concentration measurements are still being evaluated and are not available for comparison. (As will be shown, the data infer that the model predictions are generally high; the existing Al_2O_3 ground-level concentrations show that the model predictions are unrealistically high. As a result, the measurements are being reevaluated before the final release.)

2. Comparisons are made only for those sites instrumented for effluent concentration monitoring (versus only dosage-instrumented sites). Although these comparisons represent only about 20 to 30 percent of the existing ground-level effluent data, they include the highest quality data.

3. The model calculations used for the comparisons are postlaunch calculations, thus making use of measured data to define model input parameters such as cloud stabilization altitude, meteorology, and cloud trajectory. Errors in forecasting meteorology have thus been reduced, and the comparisons are more representative in assessing the diffusion aspects of the model.

4. An assumed ±10° error in the trajectory of the cloud was used to generate an error band for the diffusion model.

Two types of comparisons are discussed: comparison at all sites instrumented during the four launches with the concentration monitoring instruments, and comparison at only those sites where positive HCl data were recorded.

<u>All instrumented sites</u>.- During the four launches selected for comparison, 37 surface-level sites were instrumented with effluent concentration monitoring instruments. Tables 4-IX, 4-X, and 4-XI show the comparisons for these sites. A value larger than 1 in the ratio column of the tables indicates an overprediction by the model of the effluent concentration or the dosage at the site; values less than 1 indicate an underprediction. As shown by the data, the model predictions were consistently high. If the ±10° trajectory error is assumed to be an acceptable error band for the model calculations, then table 4-XII summarizes the model-measurement comparisons. Based on the data in table 4-XII, it is easily concluded that the model predictions are consistently high or within the assumed error band but seldom low. However, it can be argued that this type of comparison should show the model predictions to be high. The reasoning for this argument is that if the model cloud trajectory is different from the measured trajectory, then there will be a large percentage of instrumented sites (since site placements were partly based on the model) where effluent concentrations are not measured but where the prediction shows measurable quantities, and hence the ratio of predicted to measured will be large. However, for these cases, few sites were instrumented in those areas where the cloud actually traveled; and, because these sites are not included in the comparison, the comparisons are biased. To help address this argument, a second type of comparison is presented.

<u>Positive HCl data sites</u>.- The same type of comparisons as those presented in table 4-IX to 4-XII will be discussed in this section, except that the instrumented sites used for the comparisons are restricted to only those sites where positive HCl data were obtained. If HCl was measured at a site, then it can be assumed that if the model satisfactorily predicted the cloud trajectory, the model-measurement comparisons are valid and are representative of the model accuracy. However, if the model did not satisfactorily predict the cloud trajectory, then the comparison results should show the model predictions to be low, and the comparison results are biased toward low model predictions. Tables 4-XIII, 4-XIV, and 4-XV show the results of the comparison for those sites of the original 37 sites where positive HCl data were obtained. Table 4-XVI summarizes these comparisons. Again, it is concluded that the model tends to predict high or within the assumed ±10° error band. Even in this biased comparison, the model predicted low only about 20 percent of the time. Based on the data of table 4-XIV and 4-XV and considering the plus-or-minus error values on the predictions, the predicted range of effluent concentrations and dosages at a given site is generally within a factor of 10 of the measured values.

In summary, for the data presented and for both types of comparisons, the model predictions are shown to be high. For those cases where the input cloud stabilization altitude and cloud trajectory agree reasonably well with the actual cloud behavior, the model appears to be accurate to within a factor of 10 for maximum HCl concentration, HCl dosage, and Al_2O_3 dosage at a given site. In conclusion, table 4-XVII is presented to show a comparison of the maximum HCl measured at surface level with the predictions for the maximum concentration occurring for a launch. Again, these data tend to support the overpredictive nature of the current model.

CONCLUSION

As previously discussed, the predictions using the NASA REED model will generally be too high. Thus, the calculated concentrations and dosages given in this section should be considered as upper limits.

REFERENCES

4-1. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Titan 3C Launch in December 1973. NASA TM X-73334, Aug. 1976.

4-2. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Centaur Launch in February 1974. NASA TM X-73335, Aug. 1976.

4-3. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the ATS-F Launch in May 1974. NASA TM X-73336, Aug. 1976.

4-4. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Helios A Launch in December 1974. NASA TM X-73337, Aug. 1976.

4-5. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Titan 3C (AF-777) Launch in May 1975. NASA TM X-73338, Aug. 1976.

4-6. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Viking A Launch in August 1975. NASA TM X-73339, Aug. 1976.

4-7. Stephens, J. Briscoe; Adelfang, S. I.; and Goldford, A. I.: Compendium of Meteorological Data for the Viking B Launch in September 1975. NASA TM X-73340, Aug. 1976.

4-8. Lavoie, R. L.: A Mesoscale Numerical Model of Lake-Effect Storms. J. Atmospheric Sciences, vol. 29, 1972, pp. 1025-1040.

4-9. Stephens, J. Briscoe; and Stewart, Roger L.: Rocket Exhaust Effluent Model for Tropospheric Air Quality and Environmental Assessments. NASA George C. Marshall Space Flight Center, July 1976.

4-10. Dumbauld, R. K.; Bjorklund, J. R.; and Bowers, J. F.: NASA/MSFC Multilayer Diffusion Models and Computer Program for Operational Prediction of Toxic Fuel Hazards. NASA CR-129006, June 1973.

4-11. Dumbauld, R. K. and Bjorklund, J. R.: NASA/MSFC Multilayer Diffusion Models and Computer Programs - Version 5. NASA CR-2631, Dec. 1975.

4-12. Briggs, C. A.: Some Recent Analyses of Plume Rise Observations. Paper presented at the 1970 International Union of Air Pollution Prevention Associations, Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee (ATDL No. 38), 1970.

4-13. Tatom, F. B.; and Griner, G.: Behavior of Clouds Produced by Short-Duration, High-Temperature Subsonic Exhausts. Science Applications, Inc., Aug. 1975.

4-14. Fick, A.: On Liquid Diffusion. Phil. Mag., vol. 4, no. 10, 1855, pp. 30-39.

4-15. Taylor, G. I.: Diffusion by Continuous Movements. Proc. London Math. Soc., vol. 2, no. 20, 1921, pp. 196-202.

4-16. Roberts. O. F. T.: The Theoretical Scattering of Smoke in a Turbulent Atmosphere. Proc. Roy. Soc. (London), Ser. A, vol. 104, 1923, pp. 640-654.

4-17. Richardson, L. F.: Atmospheric Diffusion Shown on a Distance-Neighbour Graph. Proc. Roy. Soc. (London), Ser. A, vol. 110, 1926, pp. 709-737.

4-18. Sutton, O. G.: A Theory of Eddy Diffusion in the Atmosphere. Proc. Roy. Soc. (London), Ser. A, vol. 135, 1932, pp. 143-165.

4-19. Sutton, O. G.: The Dispersion of Hot Gases in the Atmosphere. J. Meteorol., vol. 7, no. 5, 1950, pp. 307-312.

4-20. Cramer, H. E.: A Practical Method for Estimating the Dispersal of Atmospheric Contaminants. Proceedings of the First National Conference on Applied Meteorology, American Meteorological Society (Hartford, Conn.), Oct. 1957, pp. C-33 to C-55.

4-21. Cramer, H. E.; DeSanto, C. M.; et al.: Meteorological Prediction Techniques and Data System. Report GCA-64-3-G, Geophysical Corporation of America (Bedford, Mass.), 1964.

4-22. Pasquill, F.: The Estimation of the Dispersion of Windborne Material. Meteorol. Mag., vol. 90, no. 1063, 1961, pp. 33-49.

4-23. Anthes, R. A.; and Warner, T. T.: Prediction of Mesoscale Flows Over Complex Terrain. ECOM-5532, Army Electronics Command, Fort Monmouth, N.J., Mar. 1974.

4-24. Estoque, M. A.: A Theoretical Investigation of the Sea Breeze. Quart. Roy. Meteorol. Soc., vol. 87, no. 372, 1961, pp. 136-146.

4-25. Freeman, B. F.: A New Wind Energy Site Selection Methodology. Report No. SA175-621-LJ, Science Applications, Inc., 1975.

4-26. Kurihara, Yoshio: On the Use of Implicit and Iterative Methods for the Time Integration of the Wave Equation. Monthly Weather Rev., vol. 93, no. 1, 1965, pp. 33-46.

4-27. Kwizak, M.; and Robert, A. J.: A Semi-Implicit Scheme for Grid Point Atmospheric Models of the Primitive Equations. Monthly Weather Rev., vol. 99, no. 1, 1971, pp. 32-36.

4-28. Lange, Rolf: ADPIC, A Three Dimensional Computer Code for the Study of Pollutant Dispersal and Deposition Under Complex Conditions. Report No. UCRL-51462, Lawrence Livermore Laboratory, October 1973.

4-29. Pielke, R. A.: A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida. Monthly Weather Rev., vol. 102, 1974, pp. 115-139.

4-30. Sasaki, Y.: Proposed Inclusion of Time Variation Terms, Observational and Theoretical, In Numerical Variational Objective Analysis. J. Meteorol. Soc. Japan, vol. 47, no. 2, 1969, pp. 115-124.

4-31. Sasaki, Y.: A Theoretical Interpretation of Anisotropically Weighted Smoothing on the Basis of Numerical Variational Analysis. Monthly Weather Rev., vol. 99, no. 9, 1971, pp. 698-707.

4-32. Shimanuki, A.: Formulation of Vertical Distributions of Wind Velocity and Eddy Diffusivity Near the Ground. J. Meteorol. Soc. Japan, vol. 47, no. 4, 1969, pp. 292-296.

4-33. Smagorinsky, J.: General Circulation Experiments With the Primitive Equations. Monthly Weather Rev., vol. 91, no. 3, 1963, pp. 99-166.

4-34. Spelman, M. J.: Atmospheric Modification by Surface Influences, Part II. Report No. 15 to the National Science Foundation, NSF GA-3956, by Pennsylvania State University, 1969.

4-35. Stephens, J. Briscoe; and Hamilton, P. A.: Diffusion Algorithms and Data Reduction Routine for Onsite Launch Predictions for the Transport of Titan 3C Exhaust Effluents. NASA TN D-7862, Dec. 1974.

4-36. Stephens, J. Briscoe, ed.: Atmospheric Diffusion Predictions for the Exhaust Effluents from the Launch of a Titan 3C, December 13, 1973. NASA TM X-64925, Sept. 1974.

4-37. Stephens, J. Briscoe: Diffusion Algorithms and Data Reduction Routine for Onsite Real-Time Launch Predictions for the Transport of Delta-Thor Exhaust Effluents. NASA TN D-8194, March 1976.

4-38. Stephens, J. Briscoe; and Sloan, Joseph C.: Meteorological Regimes for the Classification of Aerospace Air Quality Predictions for NASA-Kennedy Space Center. NASA TM X-3450, June 1976.

4-39. Gregory, G. L.; Hulten, W. C.; and Wornom, D. E.: Apollo Saturn 511 Effluent Measurements from the Apollo 16 Launch Operations: An Experiment. NASA TM X-2910, Mar. 1974.

4-40. Hulten, W. C.; Storey, R. W.; et al.: Effluent Sampling of Scout "D" and Delta Launch Vehicle Exhausts. NASA TM X-2987, July 1974.

4-41. Gregory, Gerald L.; and Storey, Richard W., Jr.: Effluent Sampling of Titan 3C Vehicle Exhaust. NASA TM X-3228, Aug. 1975.

4-42. Wagner, H. S.: Measurement of Solid Rocket Motor Effluents in the Atmosphere. AMRL-TR-75-125, Sixth Conference on Environmental Toxicology, Oct. 21-23, 1975.

4-43. Stewart, R. B.; Sentell, R. J.; and Gregory, G. L.: Experimental Measurements of the Ground Cloud Growth During the 11 February, 1974, Titan-Centaur Launch at Kennedy Space Center. NASA TM X-72820, Feb. 1976.

4-44. Gregory, Gerald L.; Wornom, Dewey E.; et al.: Hydrogen Chloride Measurements from Titan 3 Launches at the Air Force Eastern Test Range, Florida 1973-1975. NASA TM X-72832, Mar. 1976.

4-45. Susko, M.; and Kaufman, J. W.: Exhaust Cloud Rise and Growth for Apollo Saturn Engines. J. Spacecraft & Rockets, vol. 10, no. 5, May 1973, pp. 341-345.

4-46 Stephens, Briscoe J.; Susko, Michael; et al.: An Analytical Analysis of the Dispersion Predictions for Effluents from the Saturn 5 and Scout-Algol 3 Rocket Exhausts. NASA TM X-2935, Oct. 1973.

4-47. Susko, M.; Hill, C. K.; and Kaufman, J. W.: Downwind Hazard Calculations for Space Shuttle Launches at Kennedy Space Center and Vandenburg Air Force Base. NASA TM X-3162, Dec. 1974.

4-48. Stewart, Roger B.; Grose, William L.: Parametric Studies With an Atmospheric Diffusion Model That Assesses Toxic Fuel Hazards Due To the Ground Clouds Generated by Rocket Launches. NASA TN D-7852, May 1975.

4-49. Stewart, Roger B.; and Gomberg, Richard I.: The Production of Nitric Oxide in the Troposphere as a Result of Solid-Rocket-Motor Afterburning. NASA TN D-8137, Mar. 1976.

4-50. Pellett, G. L.: Washout of HCl and Application to Solid Rocket Exhaust Clouds. ERDA Symposium Proceedings, No. 41 (Conf. 741003), 1976, pp. 437-465.

TABLE 4-I.- SURFACE MAXIMUM CENTERLINE HCl CALCULATIONS FOR A SPACE SHUTTLE NORMAL LAUNCH —

MODEL 3, 7 p.m., MARCH 5, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
2 500	131.5	0.039	5.408	0.009	236.747	0.023
3 750	136.6	.486	68.645	.114	242.438	.283
5 000	139.8	.913	134.930	.225	253.541	.532
6 250	141.9	[a]1.030	162.216	.270	269.332	.600
7 500	143.5	.980	[a]164.939	[a].275	289.034	.571
8 750	144.8	.875	159.186	.265	311.927	.510
10 000	145.7	.761	149.107	.248	337.284	.443
11 250	146.5	.653	138.902	.231	364.629	.380
12 500	147.1	.557	127.801	.213	393.515	.325
13 750	147.7	.476	117.230	.195	423.643	.277
15 000	148.1	.408	108.660	.180	454.788	.238
16 250	148.6	.351	99.716	.165	486.744	.205
17 500	149.0	.305	92.198	.153	519.339	.178
18 750	149.3	.266	85.594	.140	552.477	.155
20 000	149.7	.234	80.053	.130	586.073	.136
21 250	149.9	.207	74.945	.120	620.031	.121
22 500	150.2	.185	70.470	.112	654.294	.108
23 750	150.4	.166	66.390	.104	688.821	.097
25 000	150.7	.149	63.070	.097	723.584	.087

[a]Maximum.

TABLE 4-II.- SURFACE MAXIMUM CENTERLINE HCl CALCULATIONS FOR A SPACE SHUTTLE NORMAL LAUNCH —

MODEL 3, 7 p.m., MARCH 18, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
1 250	138.7	0.011	1.618	0.003	244.748	0.007
2 500	138.3	1.220	179.474	.299	252.349	.711
3 750	138.0	[a]3.264	515.027	.858	270.713	1.902
5 000	137.7	3.942	684.405	1.141	297.858	2.299
6 250	137.6	3.783	[a]731.351	[a]1.219	331.631	2.205
7 500	137.5	3.333	719.254	1.198	370.225	1.943
8 750	137.4	2.826	679.242	1.130	412.286	1.643
10 000	137.4	2.361	628.775	1.043	456.859	1.377
11 250	137.3	1.969	577.697	.953	503.275	1.148
12 500	137.3	1.652	530.668	.867	551.071	.963
13 750	137.3	1.399	489.127	.790	599.915	.815
15 000	137.3	1.196	453.008	.719	649.572	.697
16 250	137.2	1.033	421.622	.657	699.869	.602
17 500	137.2	.901	394.223	.601	750.677	.525
18 750	137.2	.792	370.137	.550	901.898	.462
20 000	137.2	.701	348.813	.505	853.459	.409
21 250	137.2	.625	329.810	.465	905.302	.364
22 500	137.2	.560	312.765	.429	957.380	.327
23 750	137.2	.505	297.380	.396	1009.657	.295
25 000	137.1	.458	283.445	.366	1062.104	.267

[a]Maximum.

TABLE 4-III.- SURFACE MAXIMUM CENTERLINE HCl CALCULATION FOR A SPACE SHUTTLE SINGLE-ENGINE BURN —

MODEL 3, 7 p.m., MARCH 5, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
2 000	149.6	0.000	0.000	0.000	236.658	0.000
3 000	147.1	.000	.020	.000	240.877	.000
4 000	146.2	.018	2.633	.004	248.566	.011
5 000	146.3	.107	16.341	.027	259.515	.062
6 000	146.7	.228	36.448	.061	273.353	.133
7 000	147.0	.320	54.079	.090	289.674	.187
8 000	147.4	.363	65.202	.109	308.078	.212
9 000	147.7	[a].367	70.164	.117	328.231	.214
10 000	148.0	.347	[a]70.667	[a].118	349.838	.202
11 000	148.4	.317	69.498	.116	372.652	.185
12 000	148.7	.283	65.528	.109	396.465	.165
13 000	149.0	.251	61.532	.102	421.115	.146
14 000	149.3	.221	57.532	.096	446.456	.129
15 000	149.6	.195	53.727	.089	472.384	.114
16 000	150.0	.173	50.400	.083	498.811	.101
17 000	150.2	.154	47.257	.078	525.646	.090
18 000	150.5	.138	44.472	.073	552.824	.080
20 000	150.9	.112	39.836	.064	608.042	.065
22 000	151.3	.093	35.978	.057	664.148	.054
24 000	151.6	.078	32.815	.051	720.927	.046
26 000	151.9	.067	30.241	.045	778.244	.039

[a]Maximum.

TABLE 4-IV.- SURFACE MAXIMUM CENTERLINE HCl CALCULATIONS FOR A SPACE SHUTTLE SLOW BURN —

MODEL 3, 7 p.m., MARCH 5, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
2 000	145.7	0.000	0.000	0.000	210.035	0.000
3 000	144.7	.010	1.296	.002	214.781	.006
4 000	144.8	.249	32.402	.054	223.426	.145
5 000	145.4	.794	109.062	.182	235.616	.463
6 000	146.0	1.281	187.006	.312	250.873	.747
7 000	146.7	1.544	242.289	.404	268.679	.900
8 000	147.2	[a]1.607	270.350	.451	288.540	.937
9 000	147.6	1.541	[a]278.383	[a].464	310.066	.898
10 000	148.0	1.411	273.128	.455	332.942	.822
11 000	148.4	1.258	264.134	.440	356.923	.733
12 000	148.8	1.107	246.810	.411	381.799	.646
13 000	149.1	.970	230.440	.383	407.409	.565
14 000	149.4	.850	214.744	.357	433.618	.495
15 000	149.7	.747	199.853	.331	460.329	.435
16 000	150.1	.660	187.538	.310	487.465	.385
17 000	150.3	.586	175.831	.289	514.938	.341
18 000	150.6	.523	165.404	.271	542.698	.305
20 000	151.0	.424	148.082	.239	598.931	.247
22 000	151.4	.350	133.806	.212	655.886	.204
24 000	151.7	.294	121.980	.189	713.385	.171
26 000	152.0	.250	112.376	.170	771.323	.146

[a]Maximum.

TABLE 4-V.- SURFACE MAXIMUM CENTERLINE HCl CALCULATIONS FOR A SPACE SHUTTLE SINGLE-ENGINE BURN — MODEL 3, 7 p.m., MARCH 18, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
1 000	140.5	0.006	1.371	0.002	386.558	0.004
2 000	141.4	[a].197	44.773	[a].075	390.358	.115
3 000	139.9	.193	[a]45.070	[a].075	399.732	.113
4 000	139.0	.158	38.185	.064	414.284	.092
5 000	138.4	.131	32.998	.055	433.484	.076
6 000	138.0	.109	29.050	.048	456.747	.064
7 000	137.8	.092	25.940	.043	483.482	.054
8 000	137.6	.078	23.425	.039	513.150	.046
9 000	137.4	.067	21.355	.035	545.270	.039
10 000	137.3	.058	19.609	.032	579.437	.034
11 000	137.2	.051	18.128	.029	615.308	.029
12 000	137.1	.044	16.855	.027	652.604	.026
13 000	137.1	.039	15.748	.025	691.090	.023
14 000	137.0	.035	14.775	.023	730.583	.020
15 000	136.9	.031	13.916	.021	770.925	.018
16 000	136.9	.028	13.151	.019	811.992	.016
17 000	136.9	.025	12.465	.018	853.676	.015
18 000	136.8	.023	11.848	.017	895.893	.013
20 000	136.8	.019	10.777	.015	981.651	.011
22 000	136.7	.016	9.885	.013	1068.817	.009
24 000	136.7	.014	9.128	.011	1157.074	.008
26 000	136.6	.012	8.479	.010	1246.189	.007

[a]Maximum.

TABLE 4-VI.- SURFACE MAXIMUM CENTERLINE HCl CALCULATIONS FOR A SPACE SHUTTLE SLOW BURN —

MODEL 3, 7 p.m., MARCH 18, 1969

Range, m	Azimuth bearing, deg	Maximum peak concentration, p/m	Maximum dosage, p/m-sec	Maximum peak 10 minute time-mean concentration, p/m	Time of cloud passage, sec	Average cloud concentration, p/m
800	138.2	0.001	0.261	0.000	334.417	0.001
1 000	139.3	.049	9.531	.016	334.559	.028
2 000	139.3	[a].988	[a]195.411	[a].326	339.196	.576
3 000	138.3	.924	188.707	.314	350.167	.539
4 000	137.8	.737	157.673	.263	366.896	.430
5 000	137.5	.596	134.930	.225	388.636	.347
6 000	137.3	.488	117.941	.196	414.601	.284
7 000	137.1	.485	104.727	.174	444.048	.236
8 000	137.0	.339	94.150	.156	476.333	.198
9 000	136.9	.287	85.496	.141	510.918	.167
10 000	136.8	.245	78.290	.128	547.367	.143
11 000	136.8	.212	72.194	.117	585.331	.123
12 000	136.7	.184	66.975	.107	624.536	.107
13 000	136.7	.161	62.457	.099	664.760	.094
14 000	136.7	.142	58.508	.091	705.831	.083
15 000	136.6	.126	55.026	.084	747.608	.074
16 000	136.6	.113	51.933	.078	789.979	.066
17 000	136.6	.101	49.167	.072	832.855	.059
18 000	136.6	.091	46.685	.067	876.159	.053
20 000	136.5	.075	42.397	.058	963.826	.044
22 000	136.5	.063	38.830	.050	1052.607	.037
24 000	136.5	.054	35.815	.044	1142.244	.031
26 000	136.4	.046	33.234	.039	1232.550	.027

[a]Maximum.

TABLE 4-VII.- COMPARISON OF EXHAUST EFFLUENT COMPOSITION (1972 VERSUS 1976)

Species weight, percent	Space Shuttle Environment Statement, July 1972 (exit plane composition)	1976 calculations (includes plume afterburning and chemical reaction)
HCl	20.9	15.4
Cl_2	.06	1.7
CO	24.37	.05
N_2	8.5	—
H_2O	10.39	23.3
H_2	2.11	0
CO_2	4.32	33.6
NO	—	1.1
OH	.01	0
H	.01	0
Al_2O_3	28.3	24.6
$AlCl_x$	.02	—
$FeCl_x$	.1	—

TABLE 4-VIII.- MAXIMUM[a] TITAN IN-CLOUD EFFLUENTS[b]

Launches	Species			
	HCl, p/m	Al_2O_3, µg/m^3	CO, p/m	NO_x, p/b
May 30, 1974 8:00 a.m. EST	—	—	—	800
Dec. 10, 1974 2:11 a.m. EST	40	2600	≈3	—
May 20, 1975 9:04 a.m. EST	6	1500	--	435
Aug. 20, 1975 4:22 p.m. EST	6	1400	—	1400
Sept. 9, 1975 1:39 p.m. EST	2	120	—	290
Mar. 14, 1976 8:25 p.m. EST	<1	(c)	≈1	1100

[a]Maximum concentration observed; peaks for each species may not be for the same pass through the ground cloud.

[b]These concentrations were measured inside the cloud at altitudes ranging from 1000 to 3000 meters. Concentrations at ground level are listed in table C-V and never exceeded 1.3 p/m HCl.

[c]To be determined.

TABLE 4-IX.- COMPARISON FOR MAXIMUM HCl CONCENTRATION

Azimuth from pad, deg	Distance from pad, km	Predicted[a] HCl, p/m	Measured HCl, p/m	Ratio of predicted/ measured
Dec. 1974 launch				
147	7	0.27 ± 0.02	[b]<0.005	54
130	7	.01 ± .04	.35	.029
147	11.5	.15 ± .01	.022	6.8
147	4	.22 ± .02	.5	.44
147	15	.09 ± .01	<.005	18
160	5	.56 ± .17	(c)	(c)
163	12.5	.24 ± .07	<.005	48
163	14	.19 ± .06	<.005	38
165	9	.37 ± .1	(c)	(c)
May 1975 launch				
145	12	0.04 ± 0.04	<0.005	8
145	8	.03 ± .02	.05	.6
145	16	.03 ± .05	<.005	6
164	16	.21 ± .09	.02	10.5
175	16	.05 ± .04	<.005	10
163	11.8	.21 ± .09	<.040	5.3
165	6.8	.1 ± .03	<.010	10
172	8.2	.08 ± .01	<.005	16
176	13.9	.05 ± .05	.025	2

[a]The ± value indicates range of prediction assuming ±10° error in cloud path.

[b]Indicates lower detection limit of instrument; no HCl detected at site.

[c]Data not available; instrument malfunction or instrument not operated.

TABLE 4-IX.- Concluded

Azimuth from pad, deg	Distance from pad, km	Predicted[a] HCl, p/m	Measured HCl, p/m	Ratio of predicted/ measured
Aug. 1975 launch				
38	3.8	<0.01 ± 0.01	<0.008	1.25
293	4	.23 ± .13	<.005	46
58	4.9	<.01 ± .01	<.005	2
11	2.8	<.01 ± .01	<.005	2
290	6	.23 ± .13	<.005	46
89	2.2	.5 ± .42	<.005	100
282	8.4	.43 ± .01	<.005	86
288	9.1	.18 ± .1	<.005	36
22	6.3	<.01 ± .01	<.005	2
329	7.2	<.01 ± .01	.014	.71
Sept. 1975 launch				
257	2.6	0.16 ± 0.02	0.006	26.7
303	3.4	<.01 ± .01	<.005	2
290	6	.04 ± .06	<.005	8
289	3.8	.06 ± .04	<.005	12
268	6.3	.56 ± .11	<.005	112
230	3.6	.01 ± .02	.023	.43
260	7.4	.62 ± .15	<.040	15.5
241	5	.12 ± .06	.040	3
256	7.1	.47 ± .06	<.005	94

[a]The ± value indicates range of prediction assuming ±10° error in cloud path.

TABLE 4-X.- COMPARISON FOR HCl DOSAGE

Azimuth from pad, deg	Distance from pad, km	Predicted[a] HCl dosage, p/m-sec	Measured HCl dosage, p/m-sec	Ratio of predicted/ measured
Dec. 1974 launch				
147	7	33.5 ± 2.5	[b]<3	11.2
130	7	.7 ± 4.5	19.5	.36
147	11.5	27 ± 1.8	6.2	4.4
147	4	19.9 ± 1.7	15.2	1.3
147	15	21.1 ± 1.4	<3	7
147	5	57.3 ± 18.1	(c)	(c)
160	12.5	48.4 ± 14.9	<3	16
163	14	43.4 ± 13.5	<3	14.5
165	9	57.5 ± 15.5	(c)	(c)
May 1975 launch				
145	12	19.2 ± 21.3	<3	6.4
145	8	16.8 ± 11.2	1	16.8
145	16	16.7 ± 24.3	<3	5.6
164	16	104 ± 44.6	(d)	10.4
175	16	26.5 ± 22.1	<3	8.8
163	11.8	104 ± 42.6	<24	4.4
165	6.8	47.1 ± 13	<6	7.8
172	8.2	38.8 ± 1.8	<3	12.9
176	13.9	23.1 ± 22.6	1	23.1

[a]The ± value indicates range of prediction assuming ±10° error in cloud path.

[b]Dosage calculated on basis of 10-minute cloud passage at site and lower detection limit of instrument from table 4-IX. No HCl detected at site.

[c]Data not available; instrument malfunction or instrument not operated.

[d]Measured dosage less than 10 p/m-sec but greater than 1 p/m-sec.

TABLE 4-X.- Concluded

Azimuth from pad, deg	Distance from pad, km	Predicted[a] HCl dosage, p/m-sec	Measured HCl dosage, p/m-sec	Ratio of predicted/measured
Aug. 1975 launch				
38	3.8	0	<4.8	0
293	4	74.8 ± 41.1	<3	25
58	4.9	0 ± 2.3	<3	0
11	2.8	0	<3	0
290	6	74 ± 41.4	<3	24.7
89	2.2	162.4 ± 137.7	<3	54.1
282	8.4	139.1 ± 3.3	<3	46.3
288	9.1	58.4 ± 33.5	<3	19.5
22	6.3	0	<3	0
329	7.2	0	7	0
Sept. 1975 launch				
257	2.6	52.4 ± 5.8	1	52.4
303	3.4	.7 ± 2.4	<3	.23
290	6	15.8 ± 22.5	<3	5.3
289	3.8	20.1 ± 12.3	<3	6.7
268	6.3	207.7 ± 40.7	<3	69.2
230	3.6	4.6 ± 8	1.2	3.8
260	7.4	241.9 ± 58	<24	10.1
241	5.0	42.2 ± 21.6	2	21.1
252	7.1	182.5 ± 23.9	<3	60.8

[a]The ± value indicates range of prediction assuming ±10° error in cloud path.

[b]Dosage calculated on basis of 10-minute cloud passage at site and lower detection limit of instrument from table 4-IX. No HCl detected at site.

[c]Data not available; instrument malfunction or instrument not operated.

[d]Measured dosage less than 10 p/m-sec but greater than 1 p/m-sec.

TABLE 4-XI.- COMPARISON[a] FOR Al_2O_3 DOSAGE

Azimuth from pad, deg	Distance from pad, km	Predicted[b] Al_2O_3 dosage, μg	Measured Al_2O_3 dosage, μg	Ratio of predicted/measured
Dec. 1974 launch				
147	7	35 ± 3	16.7	2.1
130	7	1 ± 4	(c)	(c)
147	11.5	29 ± 2	4.3	6.7
147	4	21 ± 2	28.9	.73
147	15	19 ± 1	7.7	2.5
147	5	55 ± 17	136	.4
160	12.5	48 ± 15	13	3.7
163	14	47 ± 15	2.7	17.4
165	9	60 ± 16	4.2	14.3
May 1975 launch				
145	12	17.6 ± 19.5	6.5	2.7
145	8	14 ± 9	1.2	11.7
145	16	14 ± 21	[d]<.2	70
164	16	90.6 ± 38.8	3	30.2
175	16	22 ± 18	<.2	110
163	11.8	85 ± 35	<.2	425
165	6.8	42.5 ± 11.7	<.2	213
172	8.2	35.8 ± 2	.6	60
176	13.9	17 ± 16.7	<.2	85

[a]Data from September 1975 launch are not shown because data analysis is incomplete.

[b]The ± value indicates range of prediction assuming ±10° error in cloud path.

[c]Data not available; instrument malfunction or instrument not operated.

[d]Lower detection limit for Al_2O_3 dosage measurement.

TABLE 4-XI.- Concluded

Azimuth from pad, deg	Distance from pad, km	Predicted[b] Al_2O_3 dosage, μg	Measured Al_2O_3 dosage, μg	Ratio of predicted/measured
Aug. 1975 launch				
38	3.8	0	<0.2	0
293	4	60 ± 33	< .2	300
58	4.9	0 ± 2	.11	0
11	2.8	0	<.2	0
290	6	63 ± 35	<.2	315
89	2.2	150 ± 127	.11	1363
282	8.4	118 ± 3	<.2	590
288	9.1	56 ± 32	<.2	280
22	6.3	0	<.2	0
329	7.2	0	(c)	(c)

[a]Data from September 1975 launch are not shown because data analysis is incomplete.

[b]The ± value indicates range of prediction assuming ±10° error in cloud path.

[c]Data not available; instrument malfunction or instrument not operated.

[d]Lower detection limit for Al_2O_3 dosage measurement.

TABLE 4-XII.- SUMMARY OF EFFLUENT COMPARISON

Comparison parameter	Total number of comparison points	Number of times model calculation low	Number of times model calculation within error band	Number of times model calculation high
HCl maximum concentration	35	2	12	21
HCl dosage	35	2	9	24
Al_2O_3 dosage	26	2	6	18

TABLE 4-XIII.- COMPARISON[a] FOR MAXIMUM HCl CONCENTRATION:

POSITIVE HCl DATA SITES

Azimuth from pad, deg	Distance from pad, km	Predicted HCl, p/m	Measured HCl, p/m	Ratio of predicted/ measured
Dec. 1974 launch				
130	7	0.01 ± 0.04	0.35	0.029
147	11.5	.15 ± .01	.022	6.8
147	4	.22 ± .2	.5	.44
May 1975 launch				
145	8	0.03 ± 0.02	0.05	0.6
164	16	.21 ± .09	.02	10.5
176	13.9	.05 ± .05	.025	2
Aug. 1975 launch				
329	7.2	<0.01 ± 0.01	0.014	0.71
Sept. 1975 launch				
257	2.6	0.16 ± 0.02	0.006	26.7
230	3.6	.01 ± .02	.023	.43
241	5	.12 ± .06	.040	3

[a]Data from table 4-IX.

TABLE 4-XIV.- COMPARISON[a] FOR HCl DOSAGE: POSITIVE HCl DATA SITES

Azimuth from pad, deg	Distance from pad, km	Predicted HCl dosage, p/m-sec	Measured HCl dosage, p/m-sec	Ratio of predicted/ measured
Dec. 1974 launch				
130	7	0.7 ± 4.5	19.5	0.36
147	11.5	27 ± 1.8	6.2	4.4
147	4	19.9 ± 1.7	15.2	1.3
May 1975 launch				
145	8	16.8 ± 11.2	1	16.8
164	16	104 ± 44.6	(b)	10.4
176	13.9	23.1 ± 22.6	1	23.1
Aug. 1975 launch				
329	7.2	0	7	0
Sept. 1975 launch				
257	2.6	52.4 ± 5.8	1	52.4
230	3.6	4.6 ± 8	1.2	3.8
241	5	42.2 ± 21.6	2	21.1

[a]Data from table 4-X.

[b]Measured dosage less than 10 p/m-sec but greater than 1 p/m-sec.

TABLE 4-XV.- COMPARISON[a] FOR Al_2O_3 DOSAGE: POSITIVE HCl DATA SITES

Azimuth from pad, deg	Distance from pad, km	Predicted Al_2O_3 dosage, μg	Measured Al_2O_3 dosage, μg	Ratio of predicted/measured
Dec. 1974 launch				
130	7	1 ± 4	(b)	(b)
147	11.5	29 ± 2	4.3	6.7
147	4	21 ± 2	28.9	.73
May 1975 launch				
145	8	14 ± 9	1.2	11.7
164	16	90.6 ± 38.8	3	30.2
176	13.9	17 ± 16.7	<.2	85
Aug. 1975 launch				
329	7.2	0	(b)	(b)

[a]Data from table 4-XI.

[b]Data not available; instrument malfunction or instrument not operated.

TABLE 4-XVI.- SUMMARY OF EFFLUENT COMPARISON: POSITIVE HCl DATA SITES

Comparison parameter	Total number of comparison points	Number of times model calculation low	Number of times model calculation within error band	Number of times model calculation high
HCl maximum concentration	10	2	4	4
HCl dosage	10	2	2	6
Al_2O_3 dosage	5	1	0	4

TABLE 4-XVII.- COMPARISON OF MAXIMUM HCl CONCENTRATION (SURFACE) RESULTING FROM LAUNCH

Launch	Predicted maximum HCl, p/m	Measured maximum HCl, p/m	Ratio of predicted/measured	Distance[a] of nearest instrumented site to location of predicted maximum HCl site, km
Dec. 74	0.58	0.5	1.16	2
May 75	.23	.05	4.6	1
Aug. 75	1.21	.014	86	1.5
Sept. 75	.63	.04	15.8	.5

[a]Location of nearest instrumented site to location where HCl concentration was predicted to have occurred; site where maximum HCl was measured not necessarily closest instrumented site to location of predicted maximum. The purpose of this column is to indicate that instrumented sites were in the area where maximum HCl was predicted.

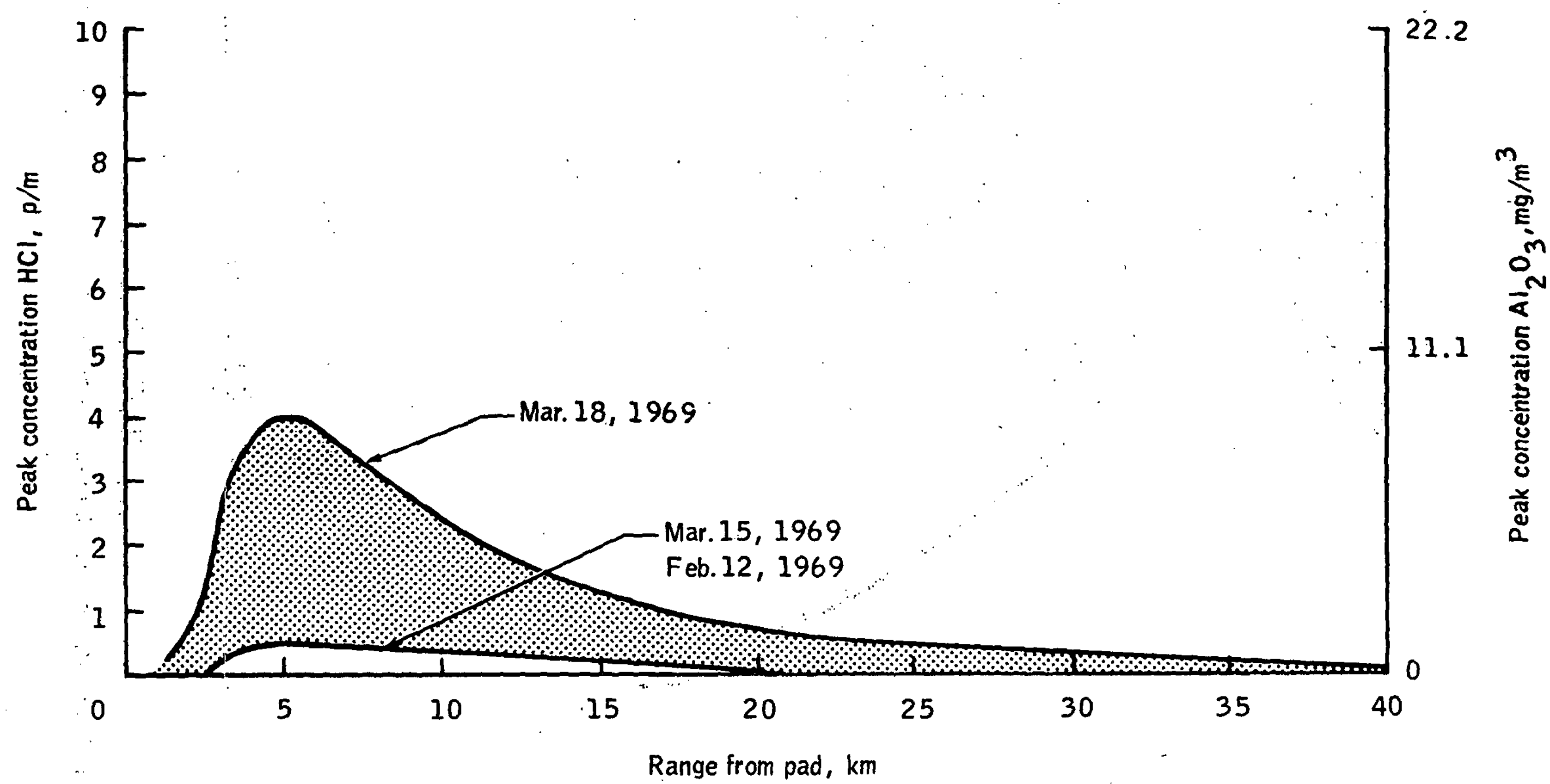


Figure 4-1.- Preliminary Space Shuttle air-quality predictions (assumes 45 launches).

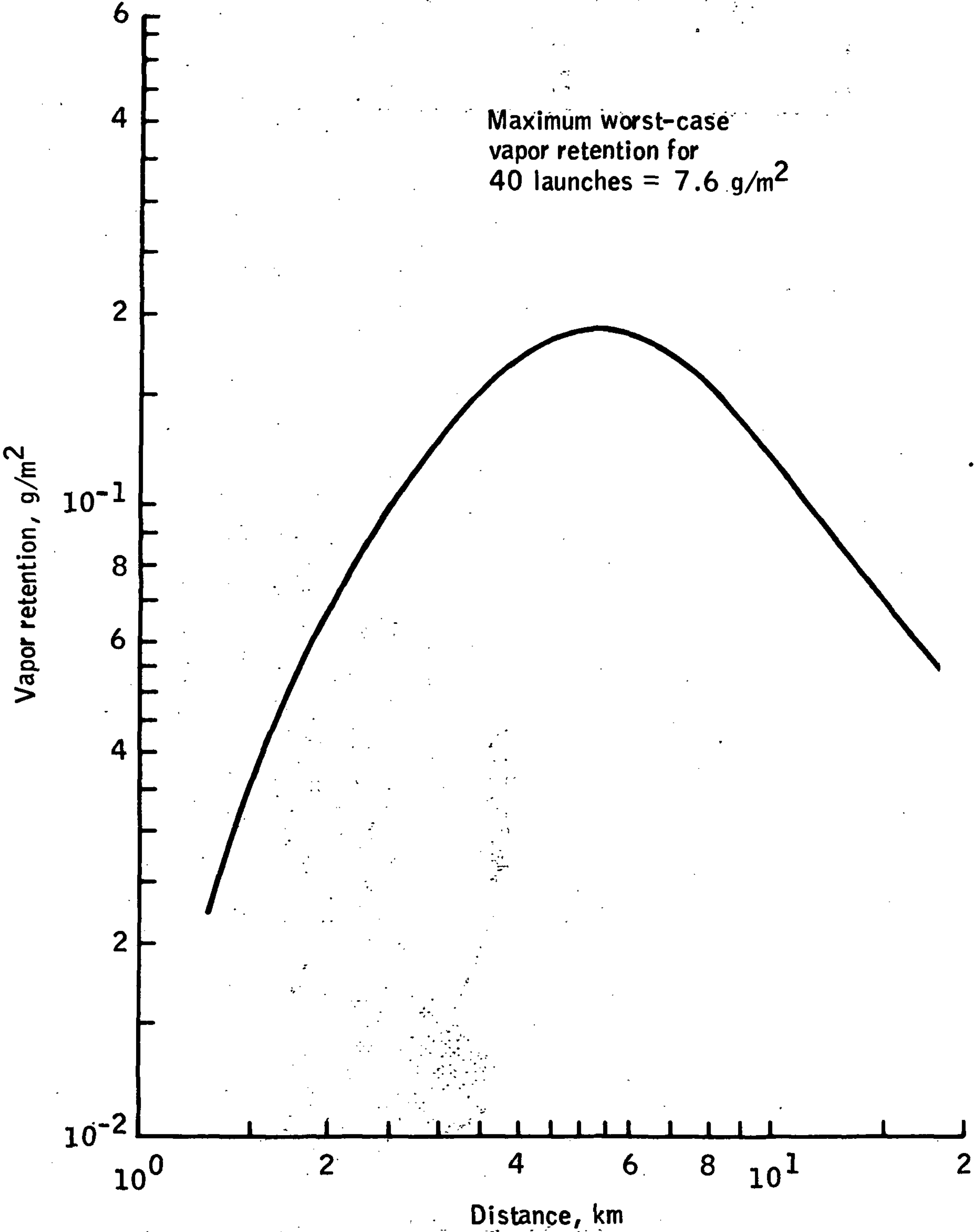


Figure 4-2.- Vapor retention at the surface versus distance from the launch pad.

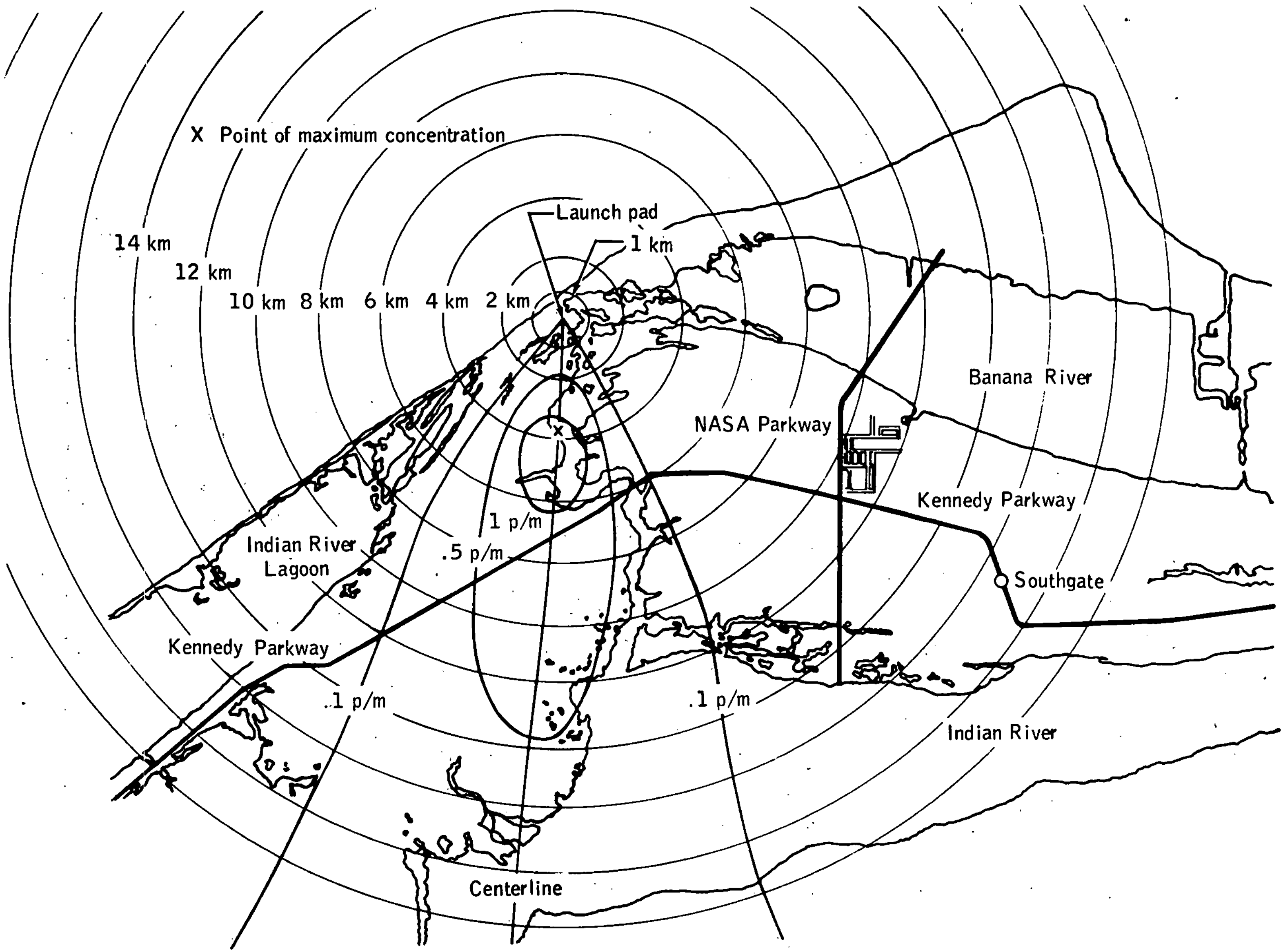


Figure 4-3.- Space Shuttle launch prediction, HCl isopleths.

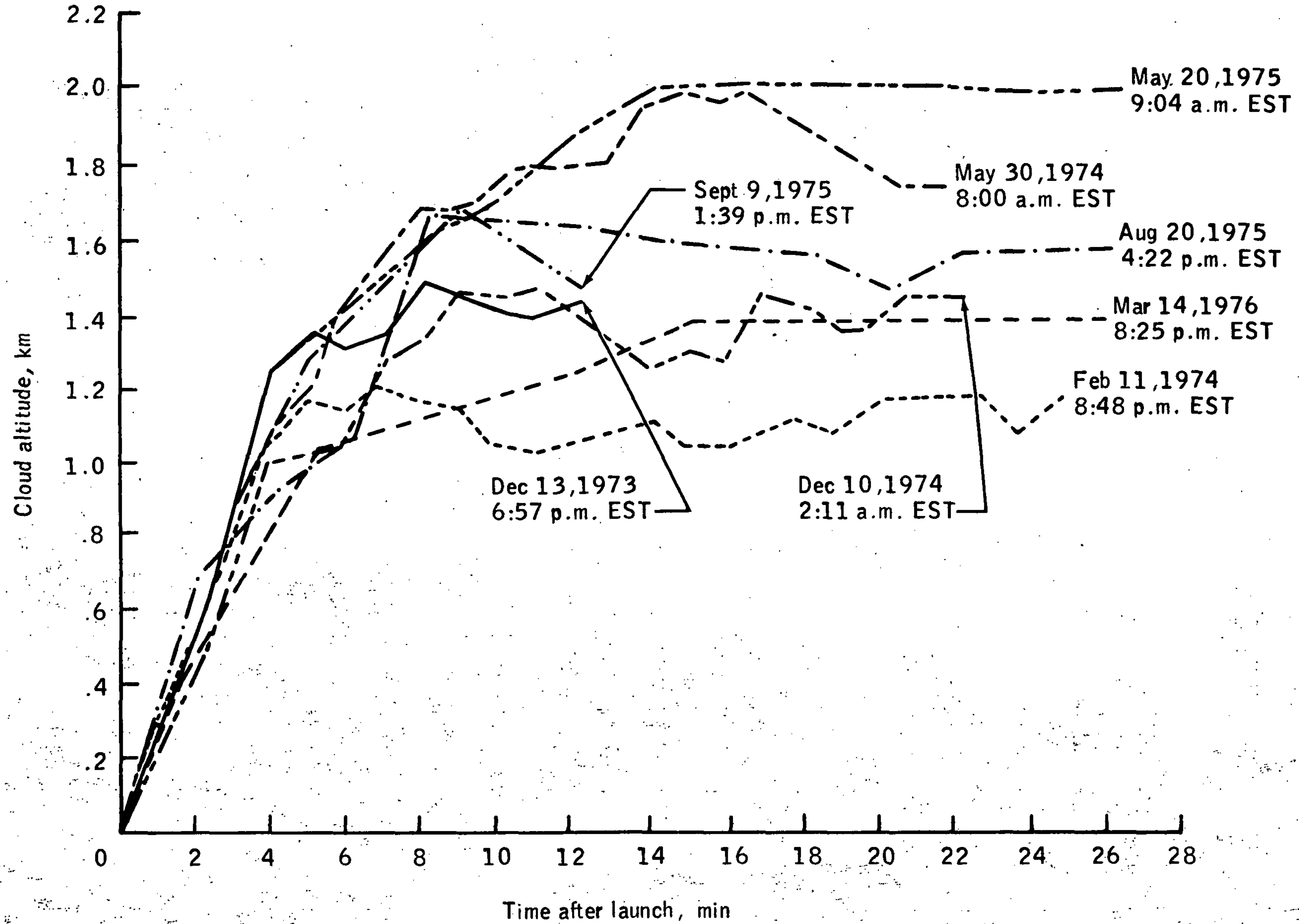


Figure 4-4.- Cloud rise and stabilization height for Titan III launches.

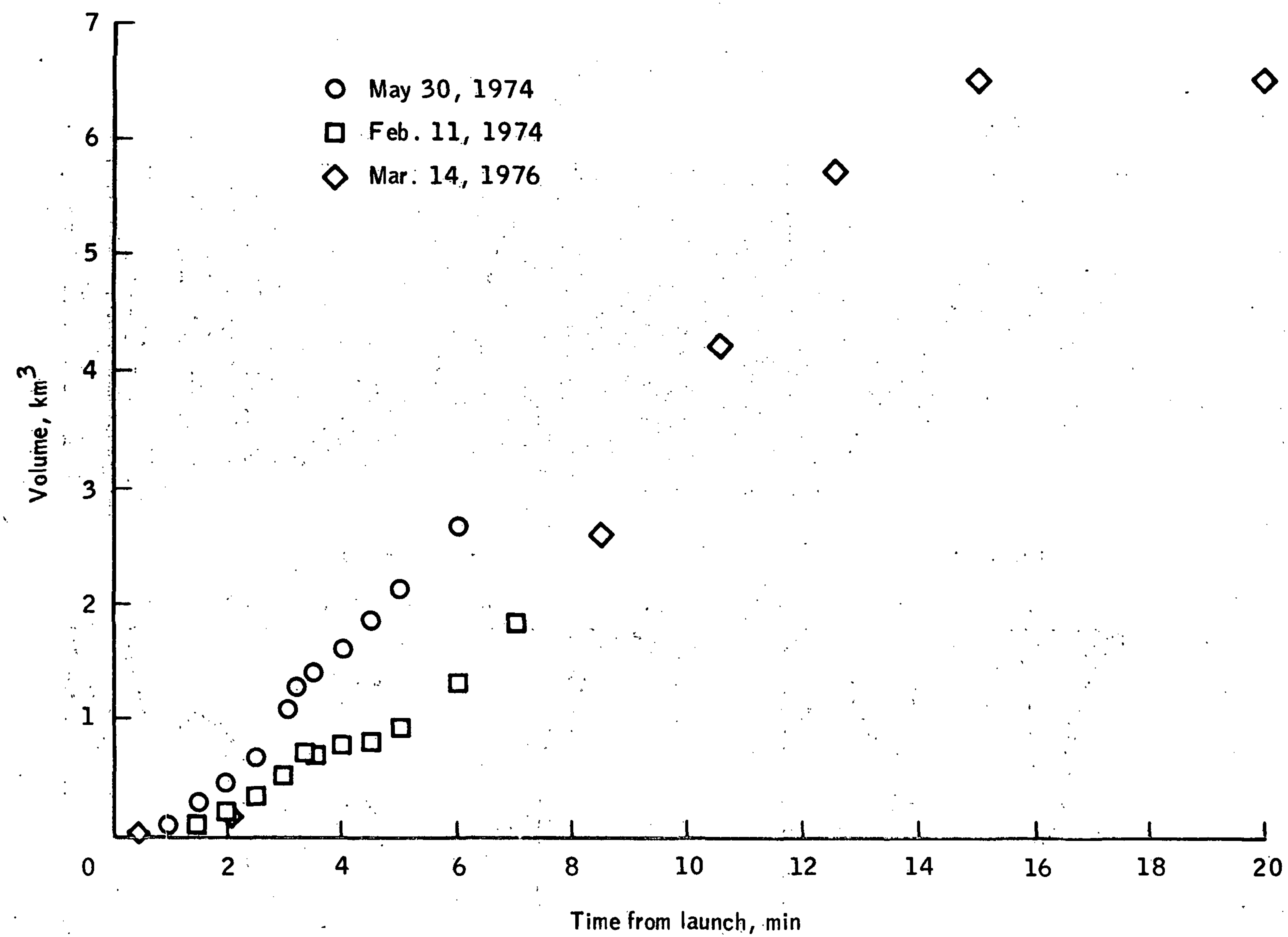


Figure 4-5.- Titan III ground-cloud volume history (measured).

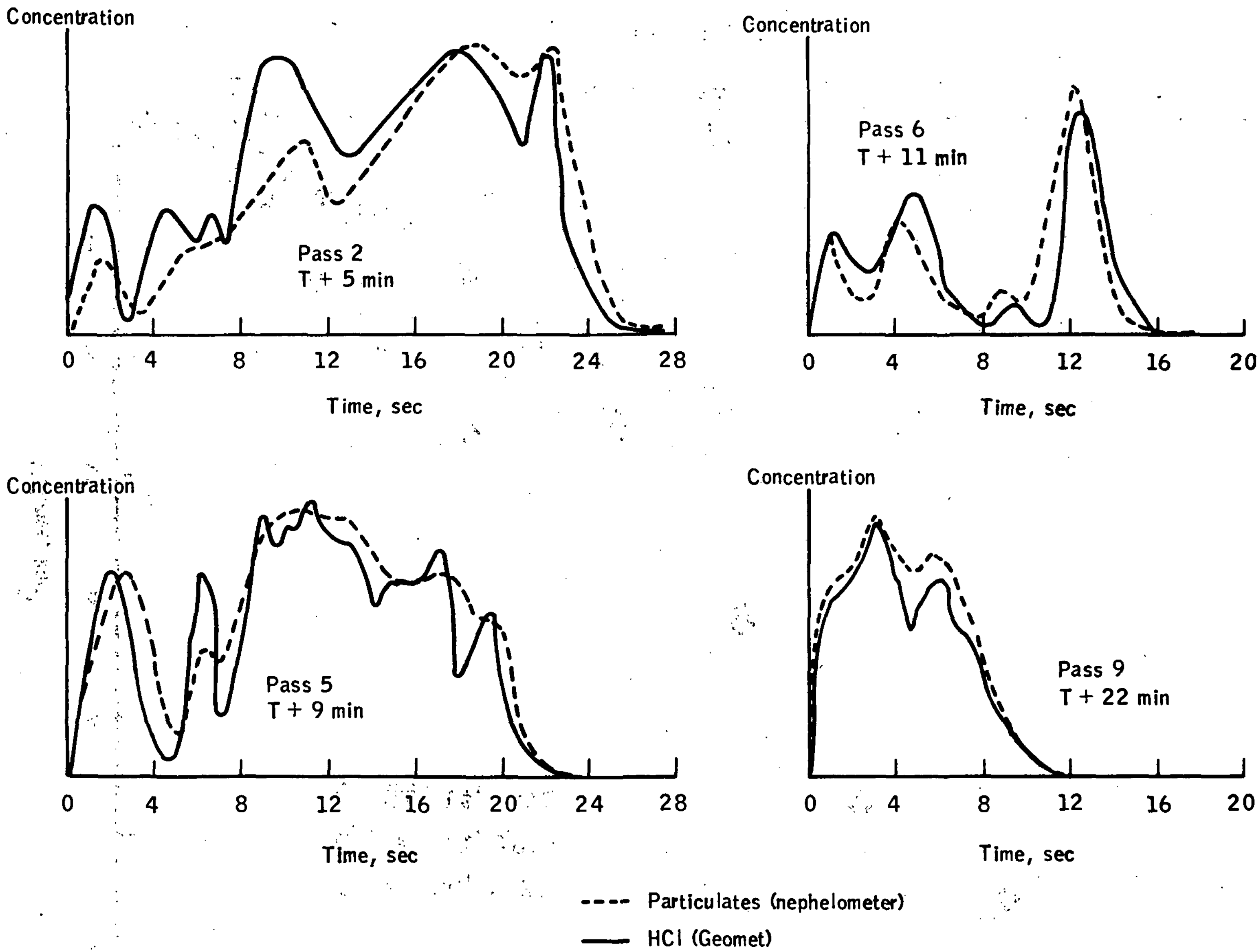


Figure 4-6.- Airborne measurements of HCl and particulates, December 10, 1974.

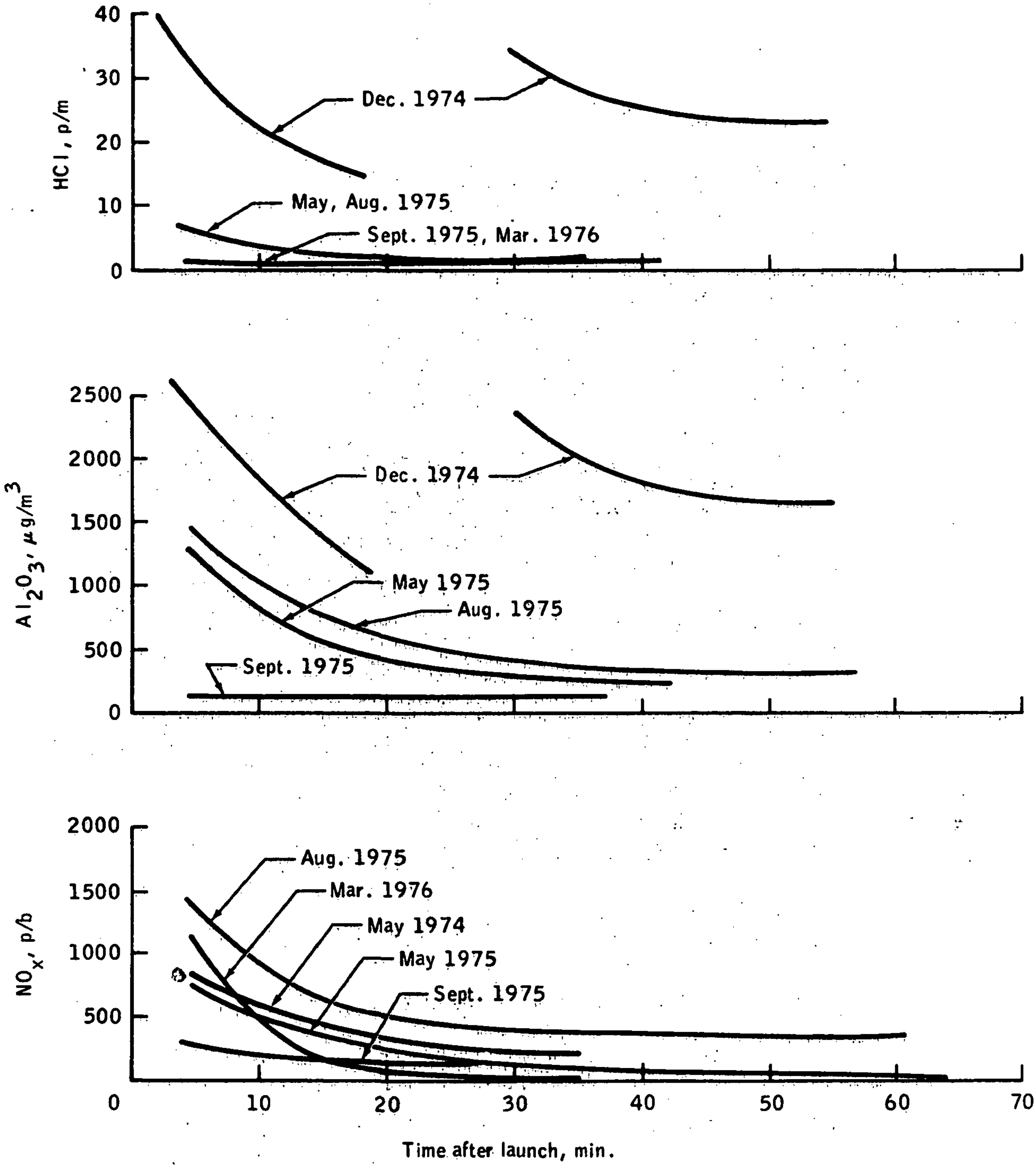


Figure 4-7.- In-cloud launch vehicle effluent measurements, 1974 to 1976.

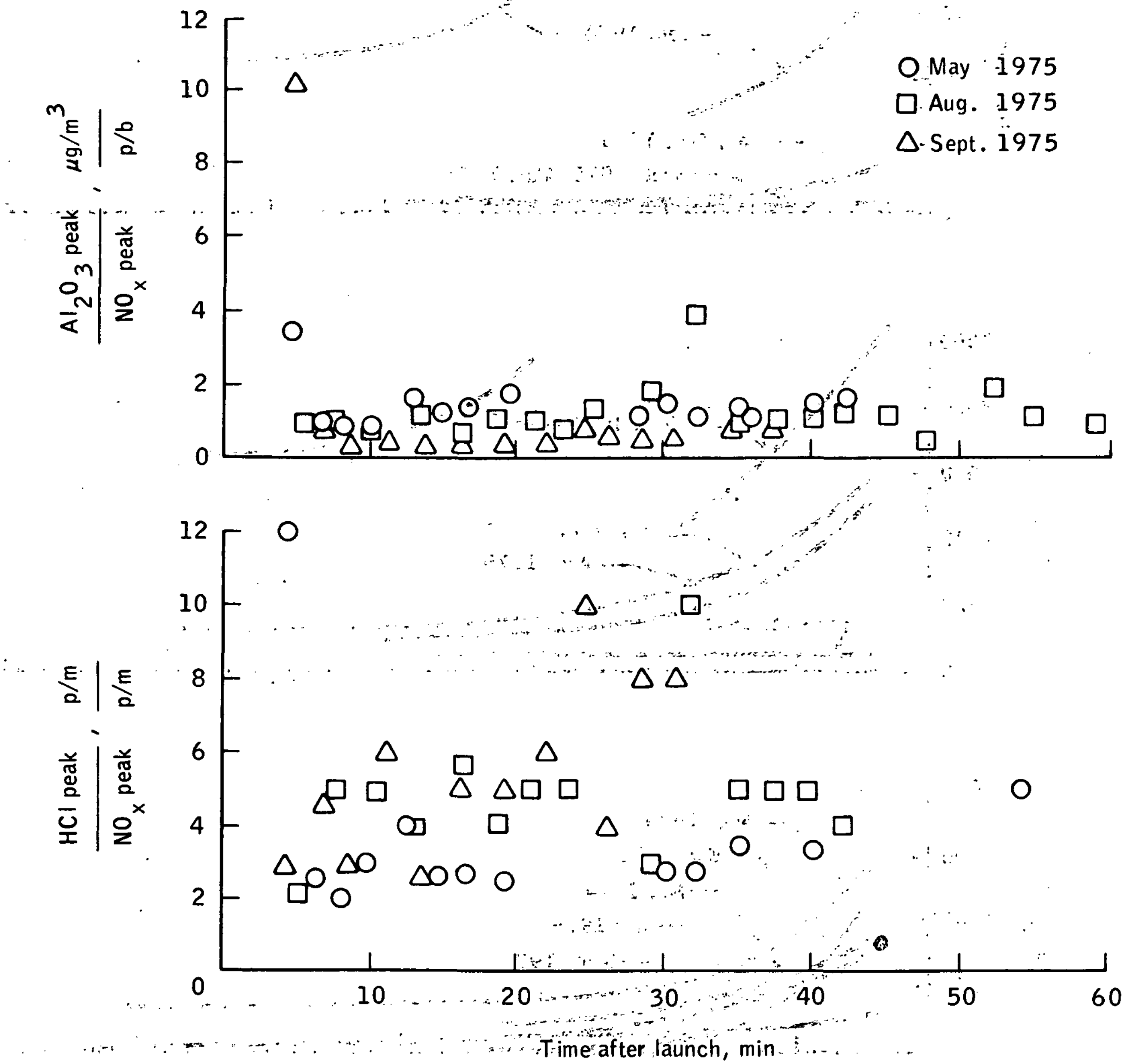


Figure 4-8.- Effluent ratios for in-cloud measurements. The nephelometer range for the Al_2O_3 particulates was from 0.2 micrometer up.

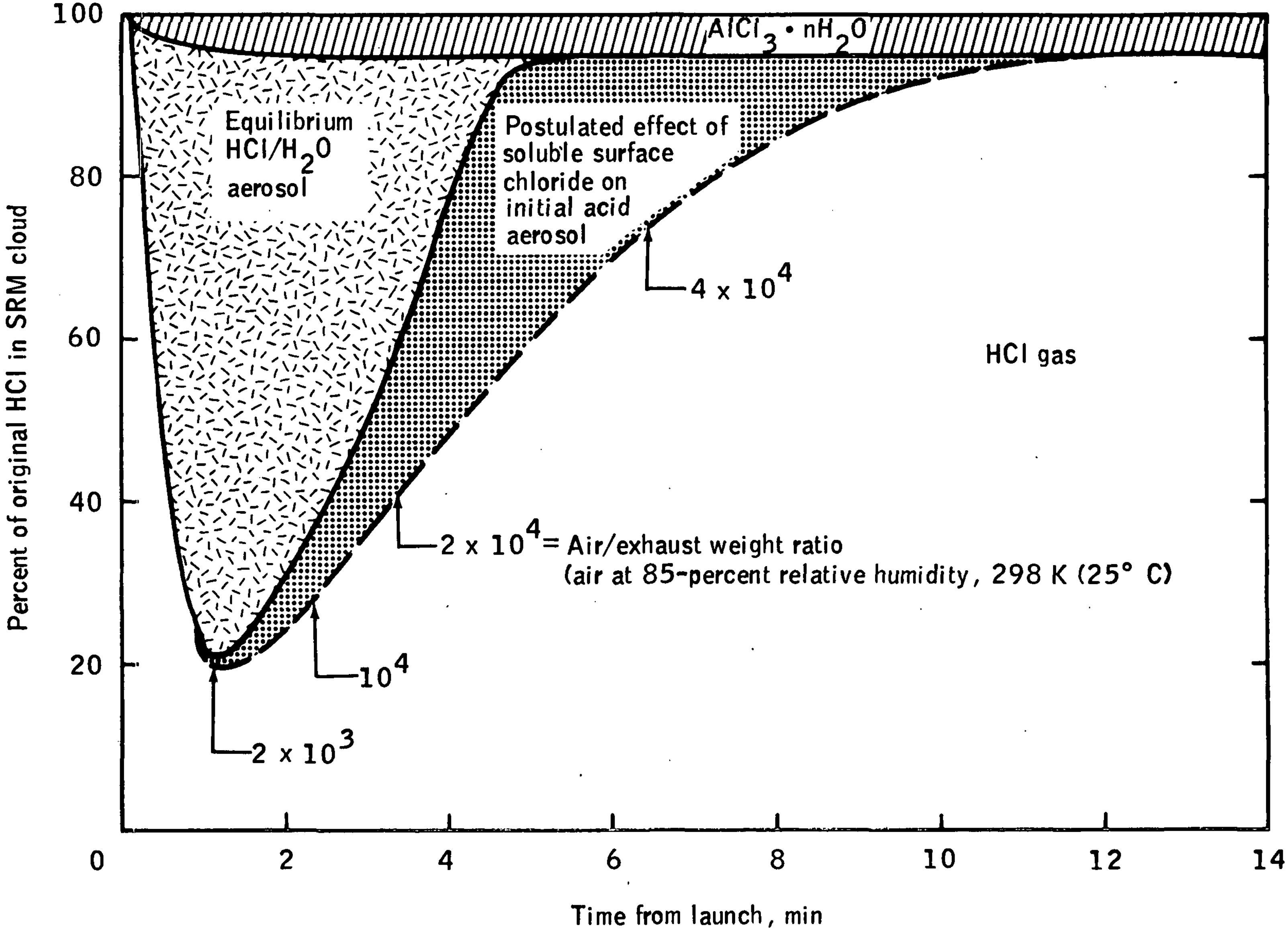


Figure 4-9.- Idealized prediction of HCl partitioning in an SRB exhaust cloud.

5. CLOUD TRAVEL

CONCERNS

The possibility that exhaust products might affect personnel, flora, or fauna around the launch site leads to a concern about where the rocket exhaust ground cloud might travel. A Shuttle launch may conceivably be postponed under certain meteorological conditions; e.g., when the predicted ground-level concentrations of hydrogen chloride gas (HCl) would approach allowable limits or when the ground cloud would be transported over unacceptable areas. Another concern is the possibility of a "washout" of HCl from the ground cloud by an overlying, precipitating cloud deck. This situation might pose a problem some distance downwind of the launch area.

TRANSPORT MODELS

The movement of the ground cloud, once it has reached its stabilization height, is primarily a function of the wind at that height. Basically, there are two ways to predict changes in the wind field in time and space: (1) by application of the primitive equations (i.e., Newtonian equations of motion, continuity equations, etc.), and (2) by diagnostic techniques that incorporate current weather observations, empiricism, climatology, and output from the synoptic-scale predictions based on the primitive equations.

The second technique is generally used in mesoscale prediction problems, primarily because models based on the primitive equations are very costly in terms of time and money. Another reason is simply that at the mesoscale, these models are limited by the lack of meteorological data. This is true even in homogeneous areas, but the NASA John F. Kennedy Space Center (KSC) launch area is characterized by inhomogeneity in the boundary layer conditions, caused by the land/sea/estuarine interfaces and the complex meteorology they generate.

Currently, cloud movement predictions are diagnostic, using the available information in a way that is primarily subjective. Empirical techniques tailored to the cloud movement problem are not well-defined; climatological studies most appropriate to this problem are almost nonexistent; and the numerical output available from the National Weather Service or the Air Force Global Weather Center primitive equation predictions could be more fully utilized.

PREDICTIONS

Cloud travel predictions for the Titan III measurements program are made before launch so that measuring devices can be deployed on the surface in a pattern most likely to be beneath the ground cloud. These predictions are usually made starting 1 day before launch and then are periodically revised as new data become available or as the need arises. Prediction accuracy depends on several factors, but the characteristics of the overall weather pattern and the time of day probably have a greater bearing on forecast accuracy than all other considerations.

The average error in six Titan III launch cloud path predictions (ref. 5-1) is shown in figure 5-1. Although the sample is very small, there appears to be a steady improvement in the forecast as the forecast time becomes less. The horizontal bars show the maximum error made for each of five forecast periods. It is anticipated that, with special effort, forecast accuracy could be improved by the time of the orbital flight test. The dashed line in figure 5-1 indicates a likely forecast error if that special effort were undertaken.

The average forecast error in six Titan III launch cloud stabilization height predictions (ref. 5-1) is shown in figure 5-2. In this case, there is no obvious improvement with the shorter forecast times.

Surface temperature is an important parameter in determining cloud stabilization height. Improvements might be made in these forecasts by: (1) anticipating the surface over which the cloud will pass and (2) by developing more representative temperature profile models above those surfaces. Improved predictions in this area should also benefit the cloud path prediction problem.

The average error in surface temperature forecasts that were prepared in support of Apollo launches (ref. 5-2) is shown in figure 5-3. Forecasts were made at 5 days before launch (L - 5), L - 3, L - 2, L - 1, and L - 0.5 that were valid for the specific launch time. The data show a definite tendency to underforecast temperatures until 1 day before launch. From that time, there is little bias and the average error was approximately 1 K (1° C). The ability to predict low-level temperature and the temperature profile in the lowest several hundred meters is essential to obtain improved cloud stabilization height forecasts. This improvement should result from using the numerical prediction techniques.

MEASUREMENTS

Many operations at both the Eastern Test Range (ETR) and the Western Test Range (WTR) are weather dependent. The success of the operation, or even the ability to initiate the operation, depends on some facet of what is generally termed as "weather." These operations have certain defined weather limitations imposed because of systems design or safety.

To ensure that the weather limitations will not be exceeded, certain meteorological measurements and observations are made at the launch facilities. These locally acquired data and other data routinely available from other locations are evaluated by staff meteorologists, who then issue forecasts of those meteorological parameters pertinent to the operation. Measurements and forecasts are made at predetermined times before the initiation of the operation.

In earlier programs, the movement of the launch cloud has not been of particular importance, either because of the propellants or because of the size of the cloud. As a result, measurements important in forecasting cloud movement have not been routinely made. For Space Shuttle operations, it is believed that the ground-cloud movement can be predicted with sufficient accuracy by using those meteorological measurements, observations, and other predictive tools normally available to support launch operations.

CONCLUSIONS

The movement of the Shuttle ground cloud is important under the following circumstances: (1) high concentrations of HCl moving over unacceptable areas and (2) a Shuttle cloud moving under a precipitating cloud. It is important to determine, before launch, those times when either circumstance may occur.

A study of the forecasts for individual Titan launches suggests that the ability to identify those situations is reasonably good except for those weather regimes characterized by weak pressure gradients. Forecasting errors in these cases are usually large. These forecasts can probably be improved significantly if the trend toward general improvement in weather forecasting during the past few years continues and if an appropriate effort is made to better understand this particular forecast problem.

CLOUD TRAVEL PANEL RECOMMENDATIONS FOR PROGRAM STATEMENT REVISION

The cloud travel panel members were in agreement that the statement beginning on page 16 of the 1972 Environmental Statement be revised and that the revision should not refer to the Titan III operating procedures; that the general thrust of the original statement be preserved; and that NASA should not make a commitment about methods used to predict cloud travel or make any statement regarding the accuracy of such predictions.

The change recommended by the panel on page 16, paragraph 2, is as follows.

Extensive theoretical calculations for the Shuttle system, supported by measurements made of solid-fuel rocket launches, indicate that concentrations at ground level beneath the exhaust cloud are below the recommended 10-minute public limits. However, the principal concern in the case of normal launches is the possibility of rain washing out the HCl from the exhaust cloud in concentrations sufficient to have an adverse effect. When meteorological conditions exist that would result in a high washout probability, operational constraints may be imposed on Shuttle launches if those meteorological conditions would also transport the exhaust cloud over unacceptable areas.

REFERENCES

5-1. Stevens, J. B.: Atmospheric Diffusion Predictions for the Exhaust Effluents From the Launch of a Titan 3C, Dec. 13, 1974. NASA TM X-64925, 1974.

5-2. Stewart, R. B.; Sentell, R. J.; and Gregory, G. L.: Experimental Measurements of the Ground Cloud Growth During the 11 February 1974 Titan-Centaur Launch at Kennedy Space Center. NASA TM X-72820, 1976.

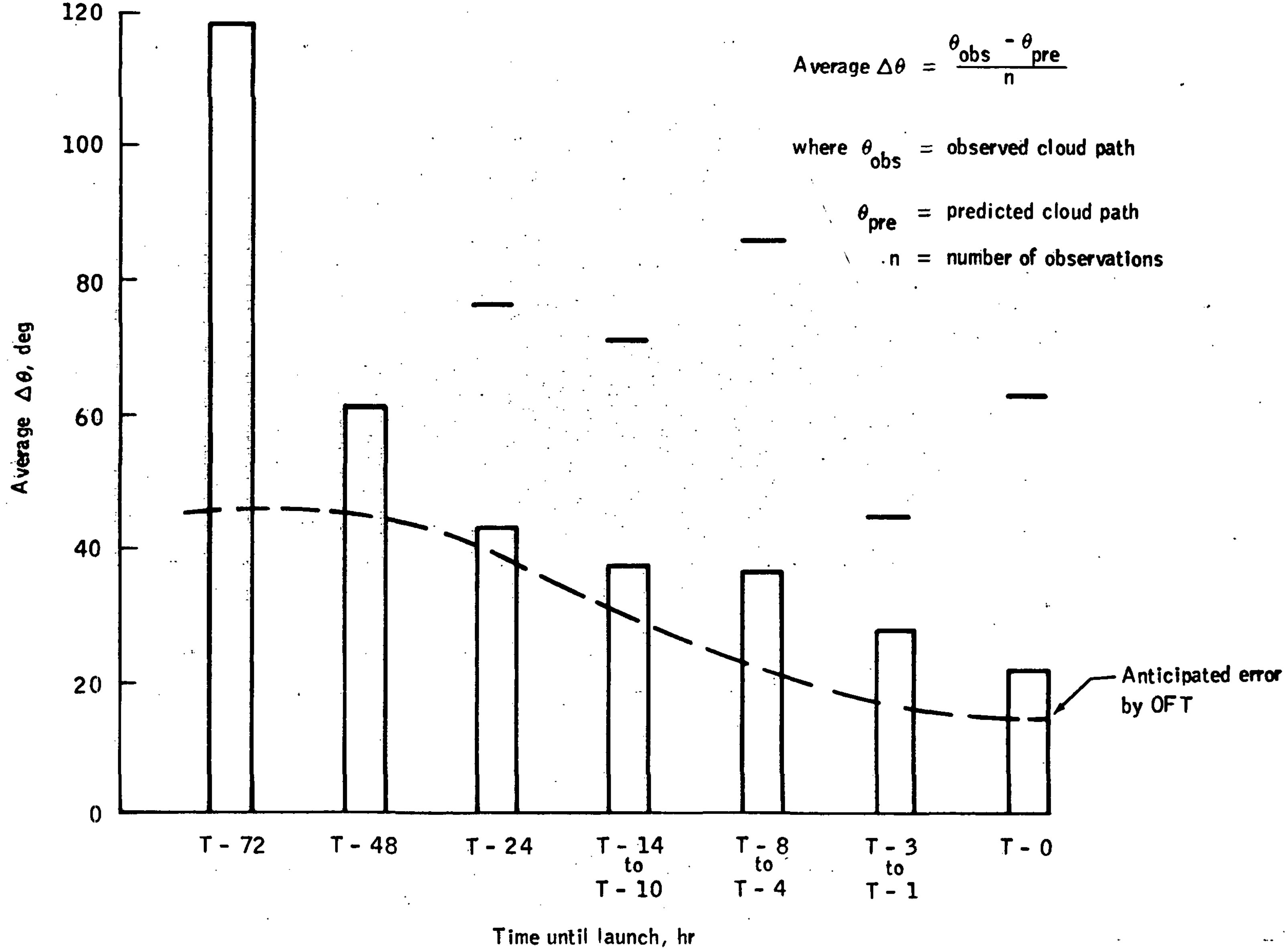


Figure 5-1.- Average error in Titan III launch cloud path prediction.

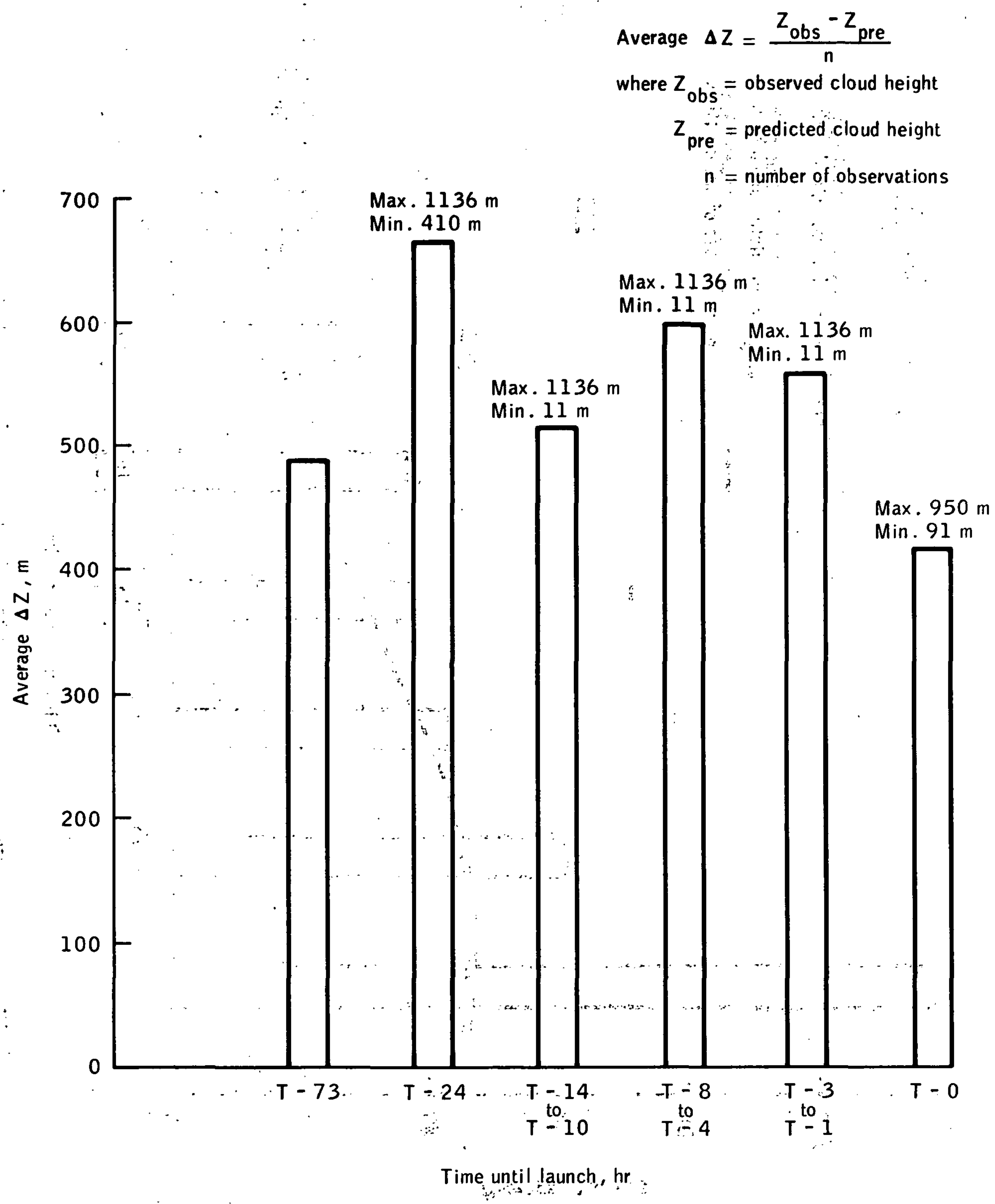
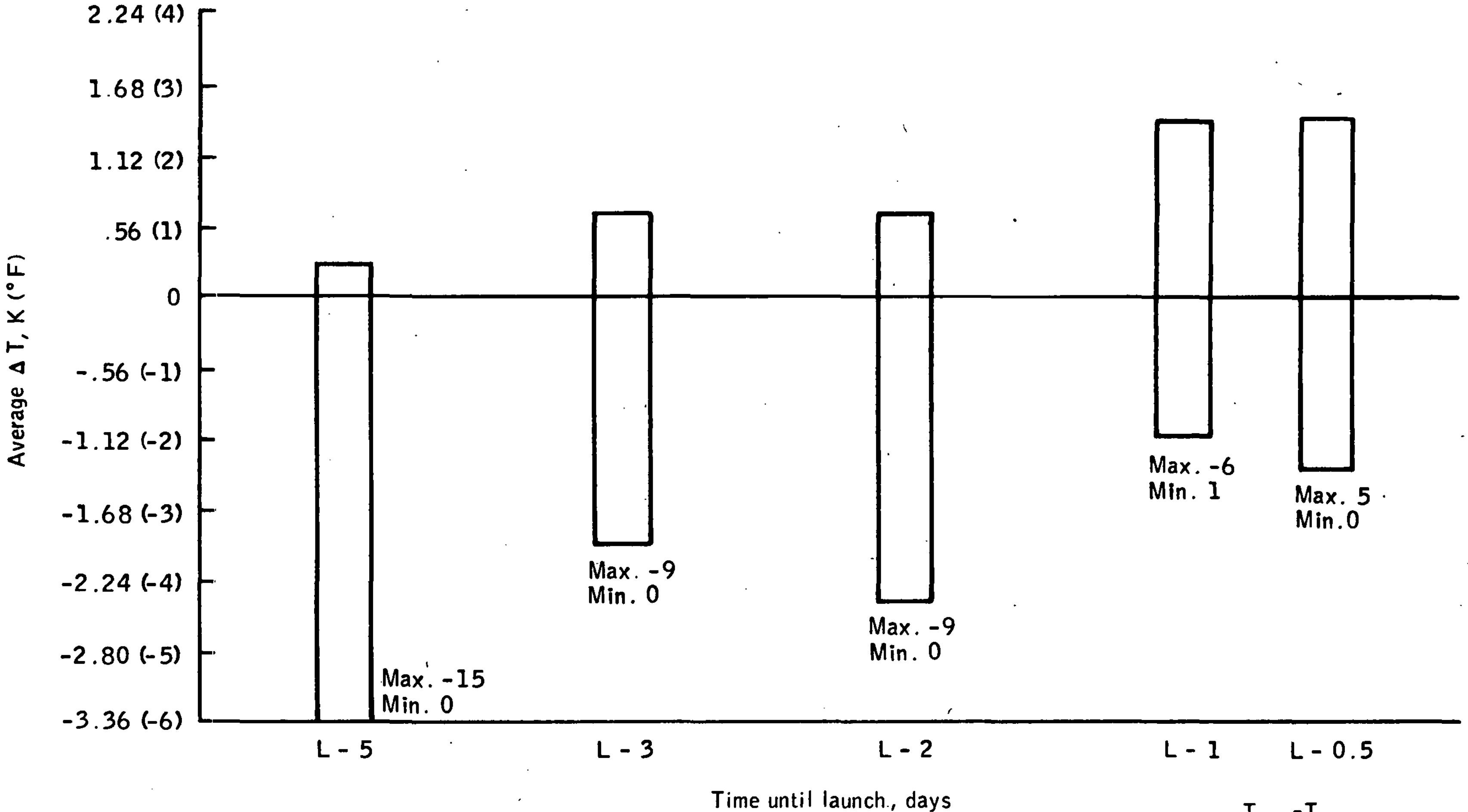


Figure 5-2.- Average error in Titan III launch cloud height prediction.



$$\text{Average } \Delta T = \frac{T_{for} - T_{obs}}{n}$$

where T_{for} = temperature forecast

T_{obs} = temperature observed

n = number of predictions

Figure 5-3.- Average error in surface temperature as a function of days before launch for Apollo missions 6 to 13 and 15 to 17.

6. RAINOUT OR WASHOUT FROM THE STABILIZED GROUND CLOUD

CONCERNS

Depending on atmospheric conditions, the exhaust products from the solid rocket motors (SRM) may (1) acquire enough water to generate a light rain or mist, (2) encounter precipitation generated separately, such as frontal rain from a higher stratum of cloud or spray blown from the edges of a convective shower, or (3) be ingested into a rain-generating cloud. The rain or mist precipitated from any of these occurrences would be acidic and might cause biological and/or corrosive damage to the exposed surfaces of fruit, plantlife, and unprotected metallic structures and mechanisms. The degree of acidity of the ground-cloud-generated rain or mist relative to the local ambient conditions and the predictability of its occurrence and general location are primary concerns in the assessment of Shuttle environmental effects.

MODEL FORMULATION

The use of numerical models verified by field experiments holds promise as a means whereby many of the weather situations can be explored. However, state-of-the-art models permit prediction with a limited confidence of the occurrence of natural rain or the resultant acidity of a rain containing SRM products. A model developed for the latter by the NASA Langley Research Center (LaRC) (ref. 6-1) represents a simple idealization of the actual problem. It applies only under low to moderate humidity where substantial aqueous acid aerosol is disfavored and under stable conditions in the lower troposphere. In this model, the gaseous hydrogen chloride ($HCl(g)$) column density resulting from the exhaust source is allowed to decay as a function of distance from the launch site in accordance with model 4, version II, of the NASA George C. Marshall Space Flight Center (MSFC) multilayer diffusion model. A steady overriding rain is assumed to begin at a point that is a set distance from the launch site before the stabilized ground cloud arrives.

The potential rain pH (initial or first rain, mixing cup average rain pH) for two different rainfall rates and the seven meteorological regimes selected as typical for the NASA John F. Kennedy Space Center (KSC) area (ref. 6-2) is shown in figure 6-1 as a function of distance from the launch site. The curves shown are for the Titan III C launches, and it is evident that pH values can vary between 2.0 and 1.0 or less at a distance of 10 kilometers from the launch site. Although the corresponding Shuttle envelope of cases has not been completed, the preliminary indication from the one Shuttle case shown in figure 6-1 (labeled "SFW (Shuttle)") is that pH values at 10 kilometers should be less than 1.0. In fact, the acidity at 100 kilometers from the launch site should range between a pH of 2.5 and a value of 1.0 or less.

FIELD STUDIES

A field sampling experiment for acidic rainfall was conducted at KSC in connection with the Titan III-Viking B launch in September 1975. The results obtained represent the first documented evidence of precipitation scavenging and the resulting acidic rainfall from an SRM-launch-associated ground cloud. A convective storm intercepted the ground cloud 12 to 15 minutes after launch at about 2.5 kilometers from the launch site. Rain samples were collected at nine locations within a 5- by 5-kilometer area, and a chloride analysis indicated that $p(Cl^-)$ ranged from 1 to 3 (3550 to 35 p/m Cl^-). At the two locations where the rainfall was the heaviest, the $p(Cl^-)$ values were near unity. Supporting evidence of pH values of unity or less was obtained from the color changes on pH papers at these same locations.

A preliminary analysis of the data from the nine sites was used to construct best-fit isopleths for $p(Cl^-)$ as shown in figure 6-2. These isopleths indicate an area of approximately 5 square kilometers with $p(Cl^-)$ values of 1.5 and less centered about 4 kilometers from the launch site and an area of more than 30 square kilometers with rain of $p(Cl^-)$ equal to or less than 3.0.

It should be pointed out that these results are considered preliminary because further analyses are proceeding and because this is the first and only scientifically observed acidic rainfall event attributable to a Titan launch cloud.

EXPERIMENTAL CHAMBER STUDIES

Experimental scavenging results were obtained by the Illinois Institute of Technology Research Institute (IITRI) for MSFC from eight chamber test firings of small SRM's (ref. 6-3). The estimated effective washout coefficients for total chloride were approximately 50 percent of the values predicted by the classical Frössling correlation for the absorption of HCl(g) by 0.9-millimeter droplets at terminal velocity. Independent studies previously conducted at LaRC have confirmed the accuracy of the Frössling correlation within ±10 percent, under a variety of conditions for 3.0-millimeter droplets falling in pure $HCl(g)/N_2$ particle-free mixtures. One plausible explanation for this difference between the measured and calculated effective washout coefficient is that the aluminum oxide (Al_2O_3) particles present, together with coexisting aqueous acid aerosol, formed a partial sink for the HCl(g) and thus the amount of HCl(g) to be scavenged by the 0.9-millimeter water droplets was systematically reduced. LaRC states that they have found strong evidence that the bubblers used by IITRI also collected and measured chlorided Al_2O_3 particles with an attendant acid aerosol. Because the scavenging efficiency for the chlorided Al_2O_3 particles and acidic aerosol is approximately one order of magnitude lower than for a droplet-free cloud (ref. 6-3), partitioning of the HCl(g) into gas, chlorided Al_2O_3, and aqueous aerosol could account for the low washout efficiency.

The acidic rain potentials given in figure 6-1 were calculated using the washout coefficient determined by LaRC to be

$$\Lambda = 1.11 \times 10^{-4} R^{0.625} \text{ sec}^{-1}$$

where R is the rainfall rate in millimeters per hour. The value proposed by IITRI based on their tests is

$$\Lambda = 8.3 \times 10^{-5} R^{0.567} \text{ sec}^{-1}$$

Although the LaRC washout coefficient is 1.33 and 1.61 times that of IITRI at rainfall rates of 1 mm/hr and 25 mm/hr, respectively, the associated acidic rain pH values differ only slightly.

In conclusion, it should be noted that the IITRI chamber tests were conducted at an air-to-exhaust weight ratio of about 225, whereas measured SRM cloud dilution ratios exceed 10 000 after 3 to 5 minutes. Thus, the aerosol growth kinetics may deviate quite substantially from the actual case.

FURTHER DEVELOPMENTS

Current grants and in-house efforts are directed toward developing improved scavenging models for (1) high relative humidity conditions, where significant acid aerosol coexists with a corresponding reduced HCl(g) concentration, and (2) metastable to unstable atmospheric conditions, where convective interactions may become important or even dominant. Preliminary findings of these studies are not yet available. A reasonably complete resolution of the HCl partitioning/precipitation scavenging problem is needed for a satisfactory solution. Some of the tasks that would contribute to this are as follows:

1. Continued in-situ aircraft sampling of SRM clouds for HCl partitioning, dispersion, and SF_6 (sulfur hexafluoride) tracer studies

2. Establishment of a suitable rain sampling network at KSC and implementation of rain tracer studies under selected meteorology conditions

3. Continued study of $HCl/H_2O/Al_2O_3$ chemisorption and microchemistry in both gas-solid and aqueous systems

4. Continued development of computational methods that treat the essential microphysics and resultant scavenging for a variety of anticipated atmospheric conditions

5. Development of a methodology for a more accurate prediction of local meteorology

These tasks are either ongoing or are planned for implementation subject to a priority rating based on the availability of funding.

CONCLUSIONS

A simple, idealized model has been developed for low to moderate humidity levels and stable conditions in the troposphere. This model, used in conjunction with the MSFC multilayer diffusion layer, provides acidic rainfall footprints. Estimates of Shuttle-induced acidic rain pH values for typical KSC meteorological regimes show 1.0 or less at 10 kilometers from the launch site and between 1.0 and 2.5 at 100 kilometers. Acidic rain was measured scientifically for the first time in conjunction with the Titan III-Viking B launch in September 1975. Preliminary estimates indicated $p(Cl^-)$ values of 1.5 and less in a 5-square-kilometer area centered about 4 kilometers from the launch site.

Experimental chamber studies to determine an HCl(g) washout coefficient using small SRM motors and 0.9-millimeter droplets yielded a value 50 percent lower than theoretical and laboratory values for gaseous HCl. This discrepancy can be explained by considering HCl(g) absorption by the Al_2O_3/aerosol particles in the chamber. The laboratory washout coefficient determined by LaRC for gaseous HCl, which agrees within 10 percent of the theoretical value, is used. However, the chamber result will not make a significant difference to the predicted pH values already quoted.

Further work is continuing to improve the acidic rainfall model by consideration of high humidity and unstable atmospheric conditions. Verification of the modeling results will be attempted by airborne sampling of Shuttle ground clouds, SF_6 studies, soluble tracer seeding, and precipitation collection using a rain sampling network.

RAINOUT/WASHOUT PANEL RECOMMENDATIONS FOR

PROGRAM STATEMENT REVISION

At the time the panel met in May 1976, it was believed that Section 1, Part B, of the 1972 Environmental Statement needed extensive revision, primarily with respect to U.S. Air Force and NASA policy regarding launch delays due to environmental considerations. The panel believed that the following statements reflected the current state of knowledge and that any revision of Section 1 should be based on these facts.

1. Emissions from the solid rocket boosters may create temporarily toxic conditions within a few hundred meters of the launch site.

2. These emissions include HCl, Cl_2, and Al_2O_3. Acidic rainfall is a potential consequence of these emissions.

3. The adverse consequences of these products for humans, animals, and the ecological system should be spelled out for the gases by themselves and in association with Al_2O_3 and the acidic rain.

4. A similar potential exists for the currently operational Titan III system. Standard operational procedures have been adopted that defer launches if weather conditions are unfavorable for a successful mission.

5. The statement regarding similar operational constraints being imposed on Shuttle should be included only if NASA policy will indeed be similar to the U.S. Air Force policy.

6. The need for additional constraints due to both ecological and mission requirements is under investigation. As far as the panel could determine, the Titan III C and Shuttle launch delay requirements are based solely on mission and crew safety requirements.

REFERENCES

6-1. Pellet, G. L.: Washout of HCl and Application to Solid Rocket Exhaust Clouds. EDRA Symposium Proceedings, no. 41 (Conference 741003), 1976, pp. 437-465.

6-2. Susko, M.; Hill, C. K.; and Kaufman, J. W.: Downwind Hazard Calculations for Space Shuttle Launches at Kennedy Space Center and Vandenburg Air Force Base. NASA TM X-3162, 1974.

6-3. Knutson, E. O.; and Fenton, D. L.: Atmospheric Scavenging of Hydrochloric Acid. NASA CR-2598, 1975.

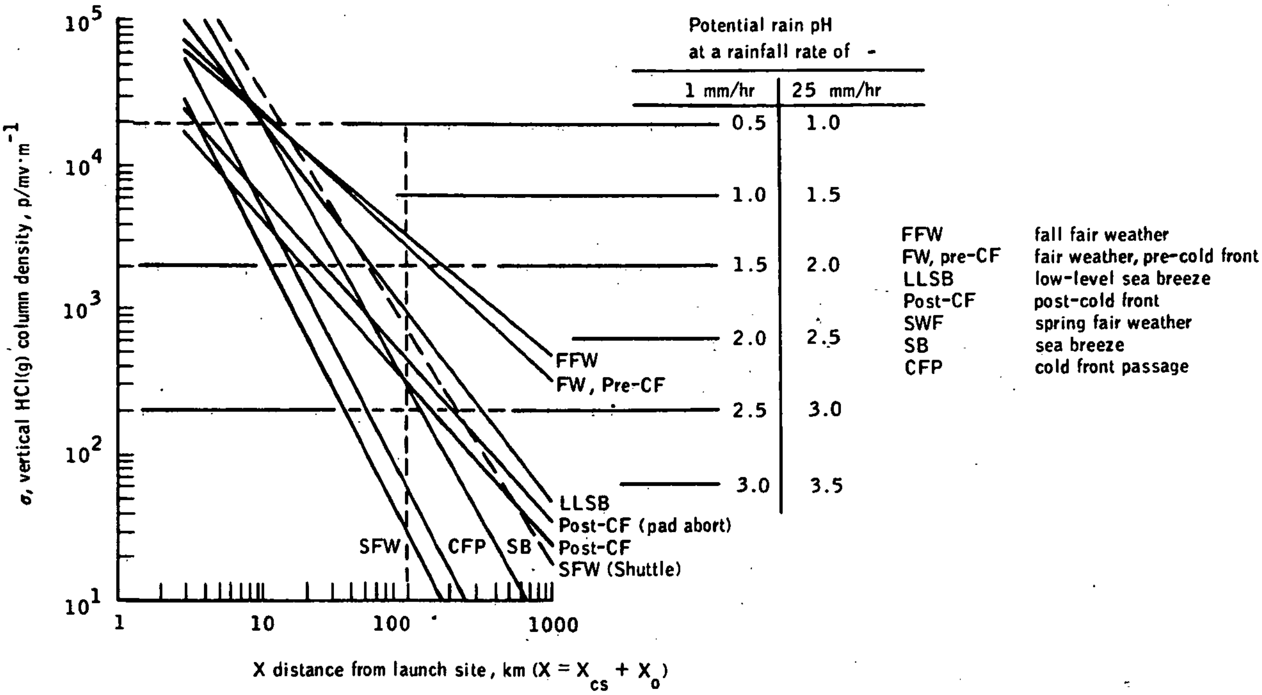


Figure 6-1.- Predicted decays of acid rain potentials for seven standard meteorologies (derived from model 4, version II, of the NASA George C. Marshall Space Flight Center multilayer diffusion model). ($X = X_{cs} + X_0$; where X_{cs} is distance from launch site to cloud stabilization or zero point, and X_0 is distance from X_{cs} to the event.)

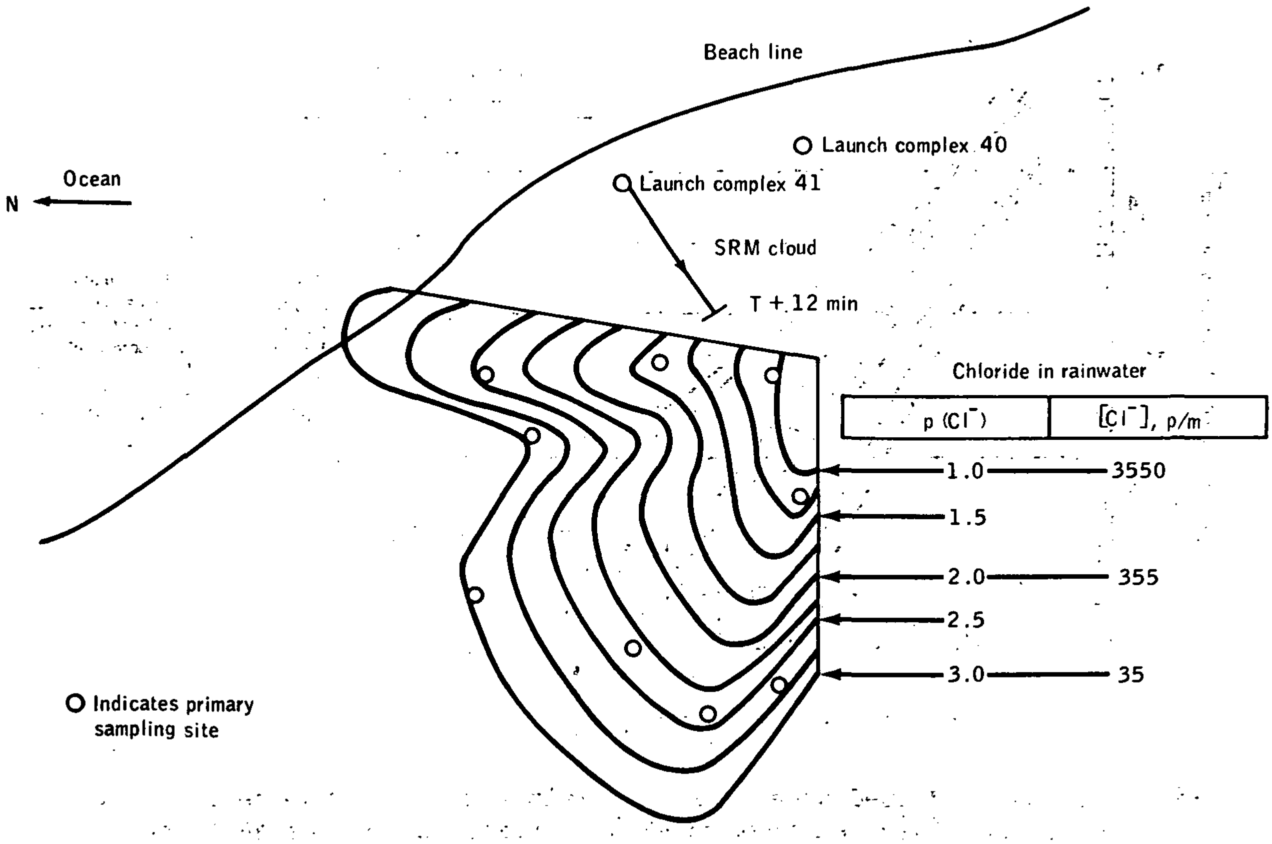


Figure 6-2.- Acid chloride footprint for precipitation scavenging of SRM exhaust cloud, Viking B launch, September 9, 1975.

7. INADVERTENT WEATHER MODIFICATION

CONCERNS

Two major concerns in the assessment of the Space Shuttle potential for weather modification are (1) the possibility that the diffusing stabilized ground cloud from Shuttle launches may modify the local weather for as long as 7 days after launch from the NASA John F. Kennedy Space Center (KSC), and (2) the cumulative effect of 40 launches per year on the weather.

MODEL FORMULAITON

A decision was made to address the concerns about weather modification by the Shuttle by eliciting a "position paper" on the subject from a team of leading atmospheric scientists. This task was contracted to the State University of New York at Albany where Dr. Volker Mohnen, Director of the Atmospheric Sciences Research Center, assembled a team of seven scientists under his leadership.

The position paper (ref. 7-1) has recently been completed, and the following excerpts summarize the results of the team's assessment of the potential for weather modification.

The following risk situations for inadvertent weather modification due to the Space Shuttle exhaust were identified.

1. An exhaust cloud encountering active convective precipitation cells could result in consequent vertical transport to the upper troposphere and the potential for acid rain. These cells would include the following conditions.

a. Sea breeze convergence during the warm season with attendant afternoon thunderstorms. Effects include possible localized hail and brief wind gusts in excess of 20 m/sec. The affected area is less than 100 square kilometers with a time scale of less than 1 day after launch (T + 1 day).

b. Frontal and prefrontal activity including squall lines with attendant thunderstorms. Effects include possible localized hail, wind gusts in excess of 30 m/sec, and tornadoes. The affected area is 100 to 500 square kilometers with a time scale of less than T + 2 days.

c. General airmass thunderstorms not associated with (a) and (b) but responding to different summer synoptic flow patterns. Effects include possible localized hail and brief wind gusts in excess of 20 m/sec. The affected area is less than 100 square kilometers with a time scale of less than T + 1 day.

d. Tropical storms in the vicinity of the Florida peninsula within 24 hours of launch time. The potential effect of a Shuttle exhaust cloud caught up in the circulation of a tropical storm is unknown in terms of inadvertent weather modification. A subsequent change of direction in such a storm might be interpreted by some people as <u>not</u> being an "act of God" with possible social and legal problems, from communities in the landfall region.

2. In the months from November to April, when advective and radiative fogs increase to a maximum, visibility in foggy situations could worsen significantly in the area affected by the dissipating stabilized ground cloud for as long as T + 1 day, particularly under windflow conditions from the southeast quadrant. The affected area could be as large as 10 000 square kilometers.

3. Minor risk is associated with an easterly flow in the lower troposphere (unless tropical disturbances are present), particularly in those situations where the atmosphere is stable under those conditions and clouds do not reach the level where ice-phase processes are operative. However, overseeding of warm clouds with cloud condensation nuclei (CCN) could result in a very significant reduction of precipitation over the entire area affected by the dispersing cloud. The effect diminishes after T + 1 day. (The criteria are a shallow, warm cloud system and no ice phase.)

4. Stagnating anticyclonic conditions could reduce dispersion of the stabilized ground cloud. A lack of clouds is normally associated with conditions of this type. The effect is therefore restricted visibility and solar energy reduction. This constitutes a nuisance and conceivably might violate Environmental Protection Agency (EPA) standards. On rare occasions, airmass thunderstorms may develop, particularly along the sea breeze convergence zone, under stagnant anticyclonic conditions during the warm season. The risk would then be equivalent to that in paragraph 1(c).

5. Possible modification of a major hurricane located east of the Florida peninsula at the time of launch could occur. Air from the launch site would be involved in the storm circulation and might indeed cause some modification that would produce unknown results. Any subsequent veering of such a storm would undoubtedly cause serious social and legal problems.

6. The cumulative effect for the projected 40 launches per year, assuming a lapse of several days between launches, is considered negligible.

7. The risk and effects are minimal when a strong, westerly wind system extends through the lower troposphere.

Certain weather conditions warrant launch rescheduling because of risk of (1) the possible effects on hurricanes, (2) hail formation and lightning activity, (3) strong wind developments, and (4) the intensification of high rainfall rates.

CONCLUSIONS

The results of the assessment of the potential for inadvertent weather modification by the Space Shuttle indicate that the stabilized ground cloud from individual launches could modify local weather for as long as T + 2 days. Except for advective and radiative fogs, the area affected is less than 500 square kilometers. Thus, no long-range, large-area weather modification is envisaged. Also, the cumulative effect of the maximum number of launches scheduled in a year is insignificant as a weather modifier.

REFERENCE

7-1. Bollay, E.; et al.: The Potential of Inadvertent Weather Modification of the Florida Peninsula Resulting From the Stabilized Ground Cloud. Report no. 1 (NASA Contract NAS 9-14940), Institute of Man and Science (Rensselaerville, N.Y.), Aug. 1976.

8. SONIC BOOM

CONCERNS

The principal concerns associated with the Space Shuttle sonic boom are the physiological and structural effects generated by the Shuttle during ascent and by the Orbiter during entry. All the manned and unmanned space missions to date have created sonic boom disturbances (ref. 8-1). However, the Orbiter entry trajectory and recovery affects more land area than Apollo, and its airplane shape and similarity increases its public scrutiny.

MODEL FORMULATION

The procedure used to predict the Shuttle sonic boom overpressures is based on empirical techniques. Wind tunnel data on the near-field signatures of the Space Shuttle and Orbiter configurations were generated at the NASA Ames Research Center and the NASA Jet Propulsion Laboratory. These near-field signatures were extrapolated to the far field for ground-level overpressures using the method derived for the propagation of weak N-shocks (ref. 8-2). Detailed trajectory data including all linear and angular accelerations and realistic atmospheric conditions were also considered. The prediction procedure was verified during the Apollo Program. Entry sonic boom ground measurements during the Apollo 15 and 16 flights agreed within 10 percent of the predicted maximum overpressures and pulse durations for signatures generated at approximately a 35 000-meter altitude and a Mach number of 4.57 (ref. 8-1). Ascent sonic boom measurements were made during Apollo 15 and 16 as a part of the procedure development program. During Apollo 17, a major test involving six ships positioned along the ascent trajectory was conducted to verify the method over a significant range of Mach numbers. The predicted maximum overpressure was again within 10 percent of the measured value, and the prediction of the boom arrival time was excellent even though the signature was generated at 30 000 meters and a Mach number of 3.55 (ref. 8-1). The Shuttle state characteristics are quite similar to those of the Saturn V launch system and the Apollo command module entry vehicle, and the use of the procedure developed for Apollo is justified.

ASCENT PREDICTIONS

No recent ascent sonic boom overpressure calculations were available at the time of this assessment because of wind tunnel scheduling difficulties. The data for a typical Shuttle ascent given by Holloway et al. in reference 8-1 are the best currently available. The closest sonic boom experienced at sea level is almost 74 kilometers (40 nautical miles) from the launch site, and the footprint extends to more than 93 kilometers (50 nautical miles) on either side of the groundtrack. The focal zone is expected to be less than 3.7 kilometers (2 nautical miles) longitudinally along the groundtrack at its widest point and to extend to approximately 83 kilometers (45 nautical miles) on either side laterally, where it becomes narrowest (fig. 8-1). The lateral extent of the focal zone could constrain the northeasterly and southeasterly launches from the NASA John F. Kennedy Space Center (KSC) because of possible interference with populated areas (fig. 8-2). The overpressure variation ΔP as a function of range from the launch site shows a rapid decrease as the Shuttle continues its ascent to orbit (fig. 8-3).

The solid rocket boosters (SRB's) and external tanks (ET's) will also generate sonic booms. Estimates of overpressure levels are not available at this time, but it is expected that the SRB values will be lower than for the ascent. The current theory on the ET is that it will disintengrate during entry.

ENTRY PREDICTIONS

A sonic boom overpressure analysis for the first orbital flight test (OFT-1) mission has been completed for a landing at Edwards Air Force Base, California. The trajectory characteristics considered were as follows:

1. Mission Planning and Analysis Division (MPAD) nominal entry from orbit 21

2. An angle of attack of 40°/30° with a ramp to approximately 13° starting at approximately 3200 m/sec (10 500 fps) and ending at approximately 760 m/sec (2500 fps) (Thereafter, the angle of attack is variable depending on the switch point state.)

3. Entry/terminal-area-energy-management (TAEM) interface at a Mach number of 2.5 (altitude approximately 25 300 meters (83 000 feet))

4. Land overflight beginning at a Mach number of 5.6

The resulting peak overpressures are given in table 8-I and the footprint is shown in figure 8-4. It is evident that entry ground overpressures are avoided over heavily populated areas and that the peak overpressures occur over relatively small areas. A preliminary overpressure analysis for a KSC landing has been translated into the footprint shown in figure 8-5. The overpressure levels are not significantly different from the values given in table 8-I.

MEASUREMENTS

Measurements to date have been restricted to the wind tunnel. However, based on the experience and confidence in the extrapolation method engendered by the Apollo and Skylab results, it is believed that the predicted values will be within 10 percent of the actual values on the ground and/or sea levels. Ground measurements are expected to be made in conjunction with the OFT-1 mission.

CONCLUSIONS

The procedure used to predict sonic boom overpressures is based on the experience gained during the Apollo and Skylab missions. Extension to the Space Shuttle and Orbiter is valid because the state characteristics of the Shuttle and Orbiter are similar to those of the Saturn V launch vehicle and the Apollo command module entry vehicle. The maximum ascent overpressure is on the order of 287 pascals (6 psf) and occurs more than 74 kilometers (40 nautical miles) from the launch pad. An analysis of the OFT-1 mission predicts that the peak overpressure will be approximately 100.5[2] pascals (2.1 psf) and will not affect heavily populated areas. This value does not exceed the number given in the 1972 Environmental Statement for the Space Shuttle Program, which has somehow become the criterion. Further analyses are continuing for ascent from KSC, entry for a landing at KSC, and the power spectral density. The entry sonic boom overpressure levels are not expected to exceed 100.5 pascals (2.1 psf), primarily because the entry/TAEM interface has been changed from 21 300 meters (70 000 feet) and Mach 1.5 to the present 25 300 meters (83 000 feet) and Mach 2.5. Ascent sonic boom levels occur over the ocean and are not expected to cause any problems, based on previous experience with manned and unmanned space vehicles. Entry overpressure measurements for the SRB's or ET's are not available at this time.

REFERENCES

8-1. Holloway, P. F.; Wilhold, G. A.; et al.: Shuttle Sonic Boom — Technology and Predictions. AIAA Paper No. 73-1039, Seattle, Wash., Oct. 1973.

8-2. Thomas, C. L.: Extrapolation of Sonic Boom Pressure Signatures by the Waveform Parameter Method. NASA TN D-6832, 1972.

TABLE 8-I.- OFT-1 SONIC BOOM CHARACTERISTICS

[NOMINAL OFT-1 RETURN FROM ORBIT 21]

Mach number	Angle of attack, deg	Roll angle, deg	Altitude, m (ft)	Peak overpressure, Pa (psf)
Before terminal area energy management				
4.06	17.4	-57.7	32 258 (105 833)	49.80 (1.04)
3.86	16.7	-48.4	31 327 (102 779)	53.63 (1.12)
3.66	16.1	-40.2	30 226 (99 167)	56.98 (1.19)
3.46	15.4	-36.3	29 119 (95 535)	60.33 (1.26)
3.28	14.8	-36.3	28 257 (92 708)	62.72 (1.31)
3.07	14.2	-36.3	27 302 (89 575)	66.07 (1.38)
2.89	13.6	-36.3	26 552 (87 114)	67.99 (1.42)
2.67	13.0	-35.8	25 698 (84 312)	70.38 (1.47)
Terminal area energy management				
2.45	13.0	28.2	24 923 (81 768)	72.78 (1.52)
2.26	10.2	21.5	24 340 (79 857)	75.65 (1.58)
2.06	9.0	16.2	23 444 (76 917)	83.31 (1.74)
1.86	9.8	11.3	22 224 (72 914)	89.54 (1.87)
1.66	9.8	6.9	21 111 (69 263)	90.01 (1.88)
1.46	6.3	3.7	19 973 (65 527)	98.63 (2.06)
1.36	5.8	2.7	19 076 (62 584)	101.98 (2.13)
1.26	6.2	1.8	18 005 (59 073)	98.63 (2.06)

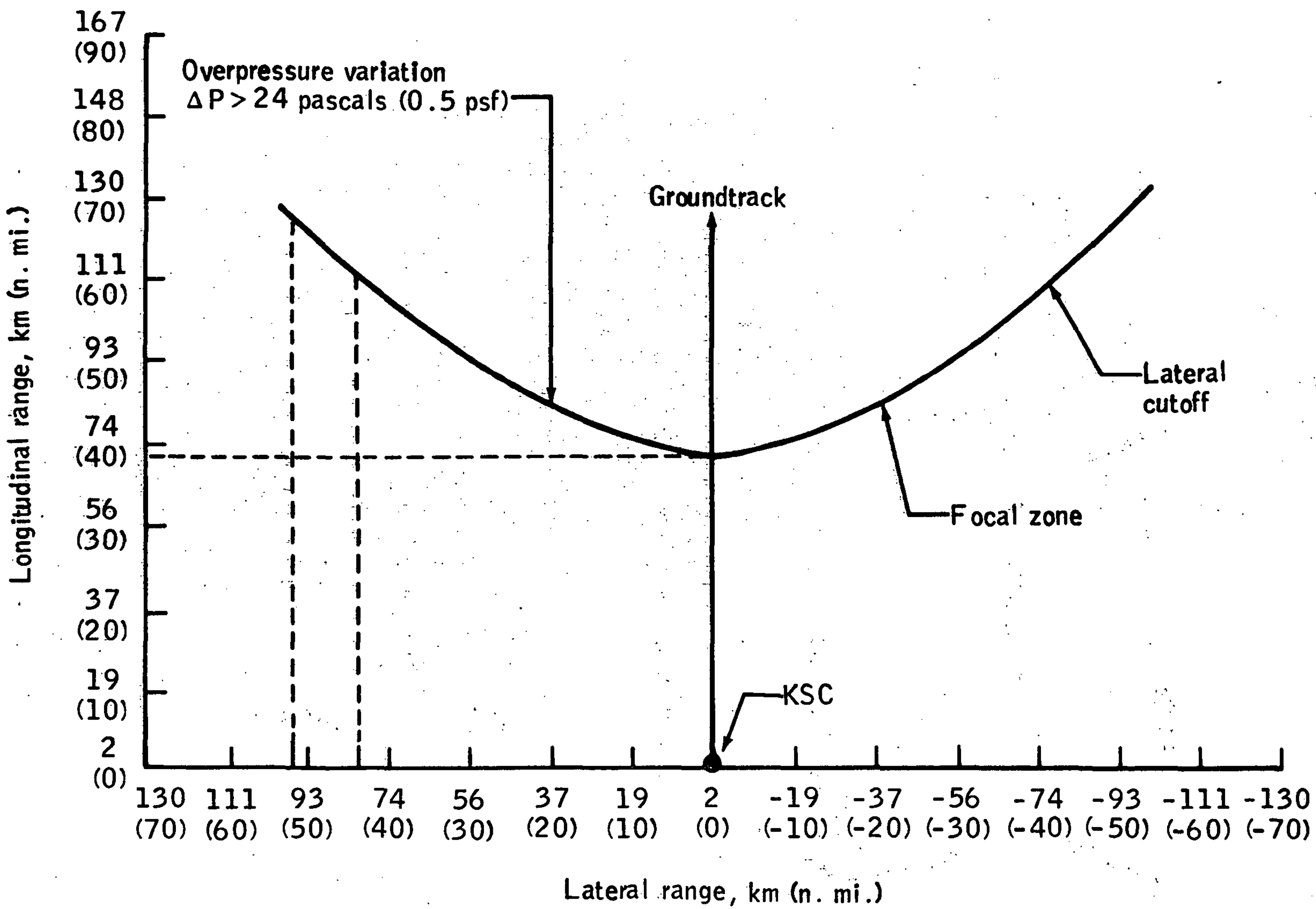


Figure 8-1.- Estimate of Shuttle ascent sonic boom footprint for a KSC launch (calculated for a launch azimuth of 6° using the 1962 Standard Atmosphere with no winds).

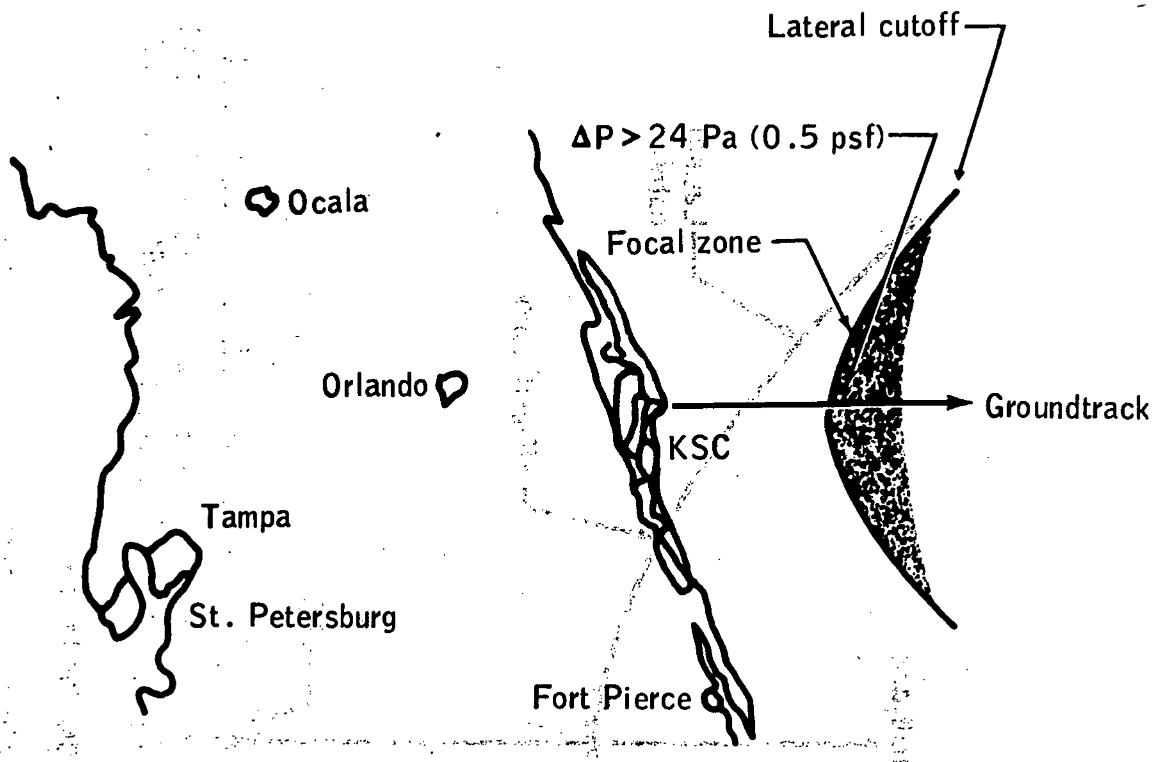


Figure 8-2.- Launch trajectory constraints imposed by sonic boom lateral cutoff.

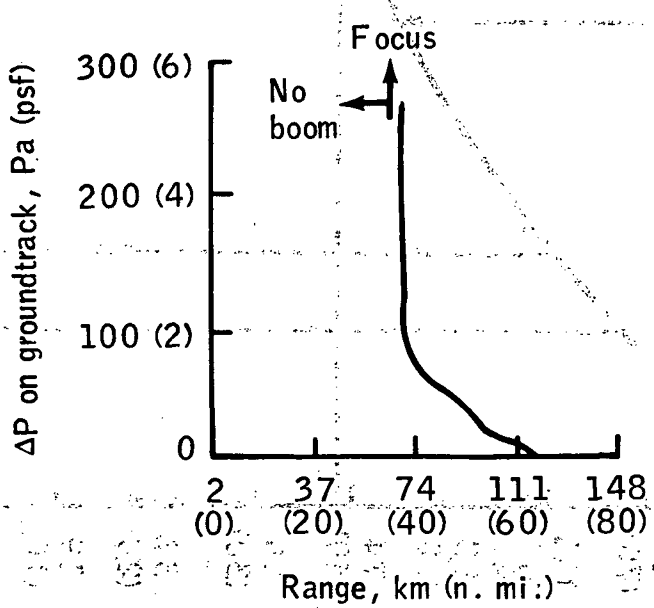


Figure 8-3.- Groundtrack overpressure variation during Shuttle ascent.

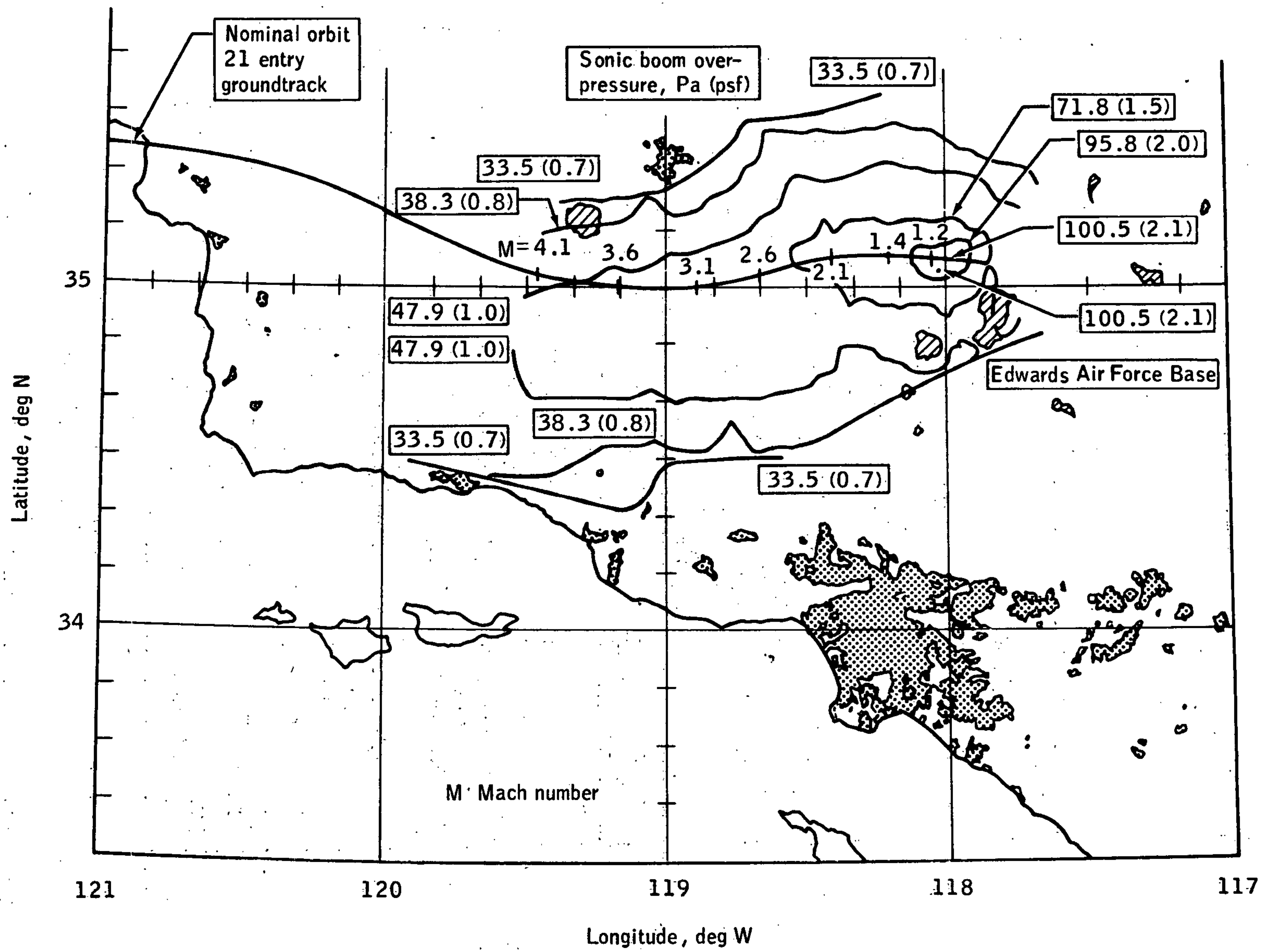


Figure 8-4.- Terminal area groundtrack for deorbit from orbit 21 for Orbiter OFT-1.

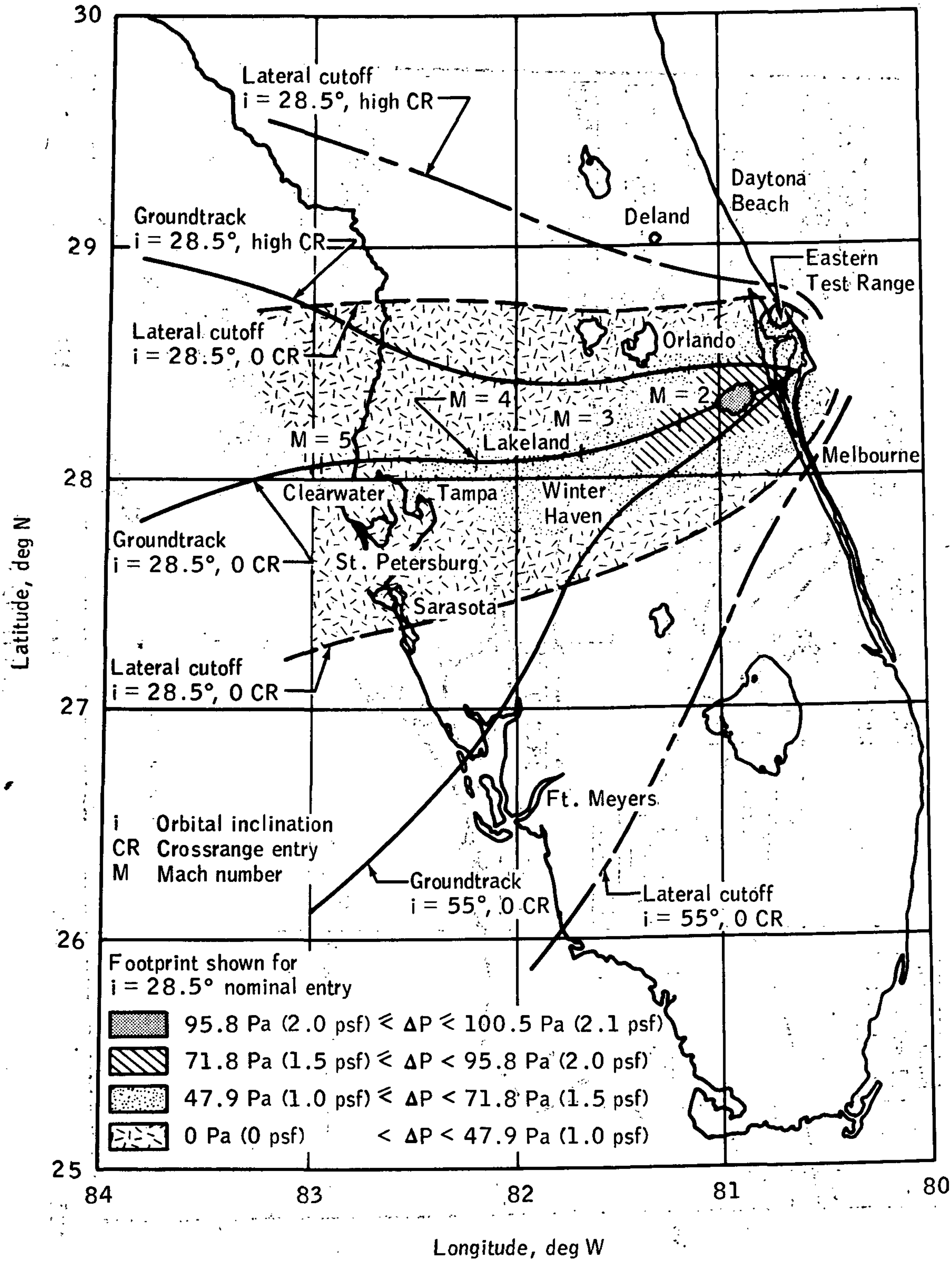


Figure 8-5.- Preliminary sonic boom ground-level overpressure footprints (Eastern Test Range entries).

9. LAUNCH NOISE

CONCERNS

The low-frequency noise generated by the Space Shuttle during ignition, launch, and ascent will cause annoyance to the public and structural damage of minor but nuisance value; it will also adversely affect wildlife, especially the endangered species, in the area of the NASA John F. Kennedy Space Center (KSC).

MODEL FORMULATION

At the time of this report, no launch noise prediction or model formulation is available for Shuttle launches at KSC other than the information provided in figure 9-1. However, the Aerospace Corporation has published an acoustic analysis for Shuttle operation at Vandenberg Air Force Base (ref. 9-1) that is pertinent for KSC also. Figure 9-2 shows the estimated Shuttle lift-off octave-band sound-pressure levels at approximately 10 500 meters (35 000 feet) ground distance from the launch pad. The maximum level does not differ significantly from that depicted in figure 9-1. It is contended also that the Shuttle, which has a maximum lift-off thrust of 30.7×10^6 newtons (6.9×10^6 pounds), will pose less of a problem to the uncontrolled population and wildlife than the Saturn V, which had a lift-off thrust of 33.4×10^6 newtons (7.5×10^6 pounds). There were no complaints from the public and no reports of structural damage during the Saturn V launches, and the wildlife at KSC was not noticeably affected.

It is recognized that the frequency of Shuttle launches during the height of the operational phase may present a very different case. Therefore, a noise assessment will be made for the Shuttle and related to the available noise allowables. The Environmental Protection Agency (EPA) is in the process of evaluating a "noise description" and guidelines to be used in future noise standards and regulations (ref. 9-2).

MEASUREMENTS

Measurements of lift-off noise levels were taken during the Saturn V launches and during some Titan III C launches at KSC. These data have been used to derive predictive equations, and a comparison of the results is shown in figures 9-3 and 9-4. The predictive equations show a good correlation, and the derived Shuttle far-field noise levels in figure 9-2 are credible.

The first opportunity to take useful pre-Shuttle measurements will be during the static test firings of the solid rocket booster (SRB). Scale data are available from the 6.4-percent-scale Shuttle firings at the NASA George C. Marshall Space Flight Center (MSFC). These results are expected to be available at a later date.

CONCLUSION

No Space Shuttle noise assessment is currently available for a KSC launch. In addition, the EPA noise guidelines and regulations are not available at this time. This omission in the environmental effects assessment will be rectified at a later date.

REFERENCES

9-1. Smith, J. R.: Effects of Shuttle Noise and Exhaust Products Dispersion on Launch Site Selection at Vandenberg Air Force Base. Report No. TOR-0075 (5421-04)-9, Aerospace Corp. (El Segundo, Calif.), Mar. 31, 1975.

9-2. Rice, E. E.: Review of the EPA Environmental Noise Level Documents. Memorandum BMI-NLVP-ICM-74-60, Battelle Columbus Laboratories, Nov. 1974.

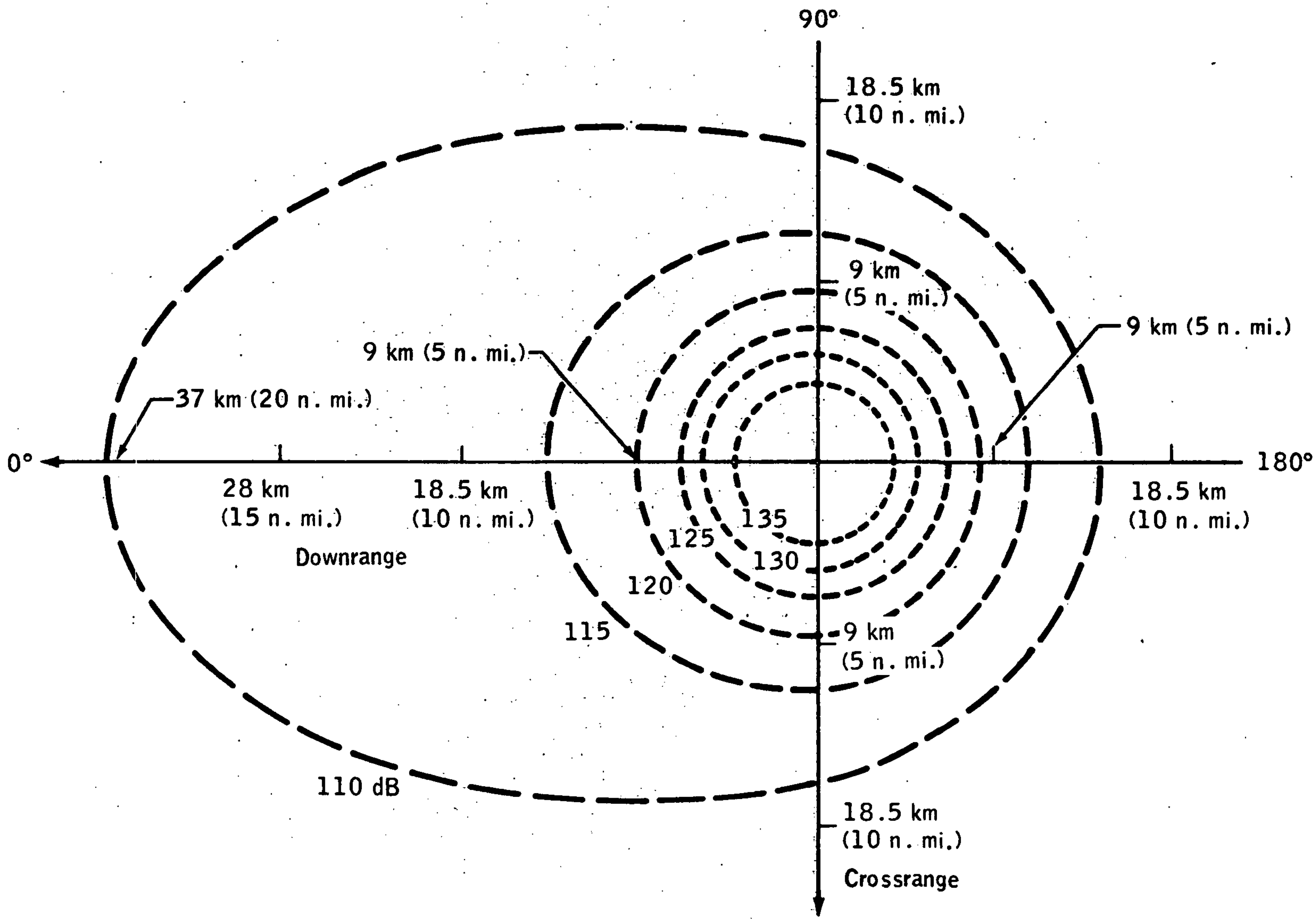


Figure 9-1.- Ground-plane maximum overall sound-pressure-level contours for Shuttle launch (29.4 × 10^6 newtons (6.6 × 10^6 pounds) thrust).

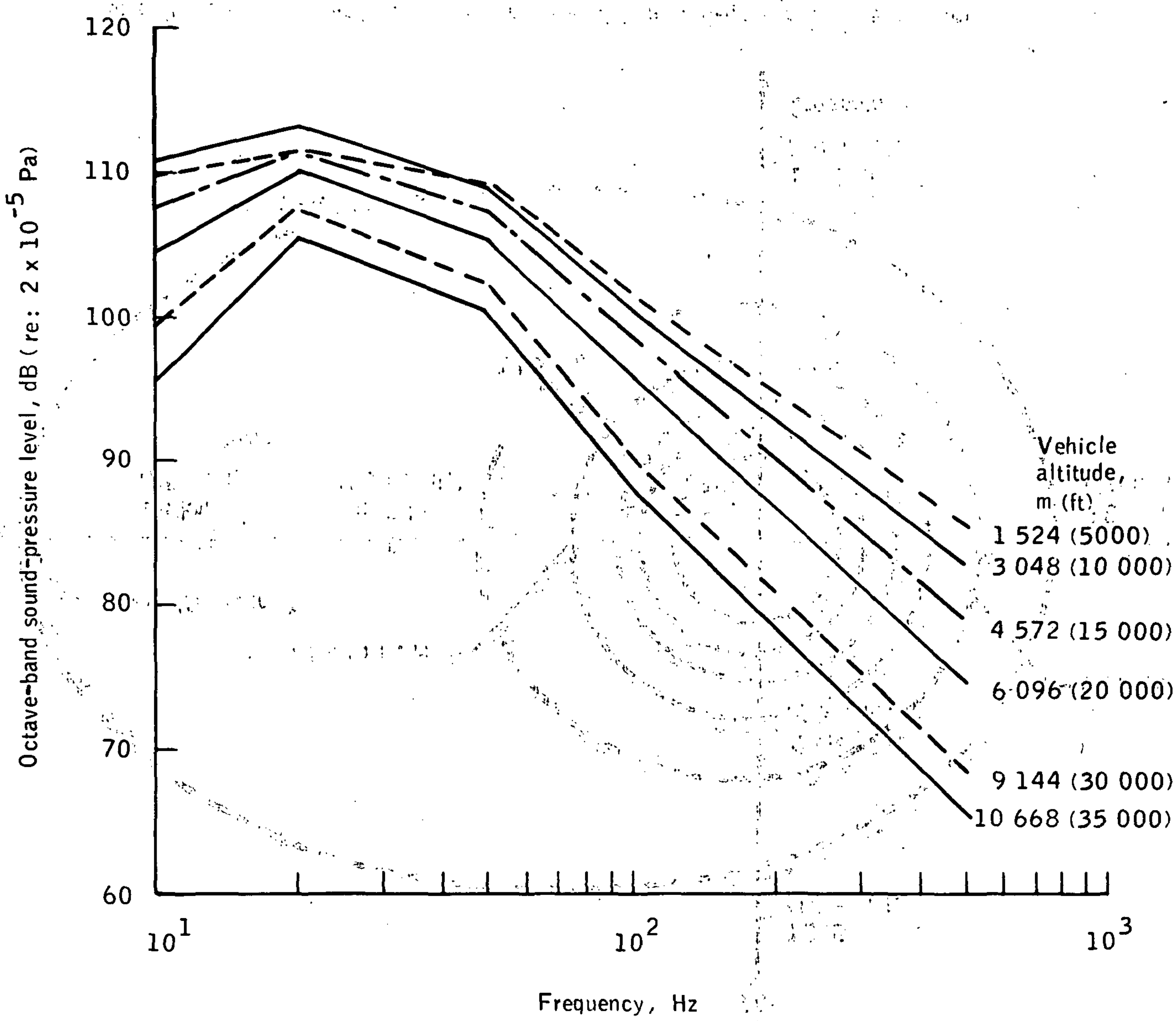


Figure 9-2.- Estimated Shuttle lift-off octave-band sound-pressure levels at 10 500 meters (35 000 feet) ground distance from the launch pad (ref. 9-1).

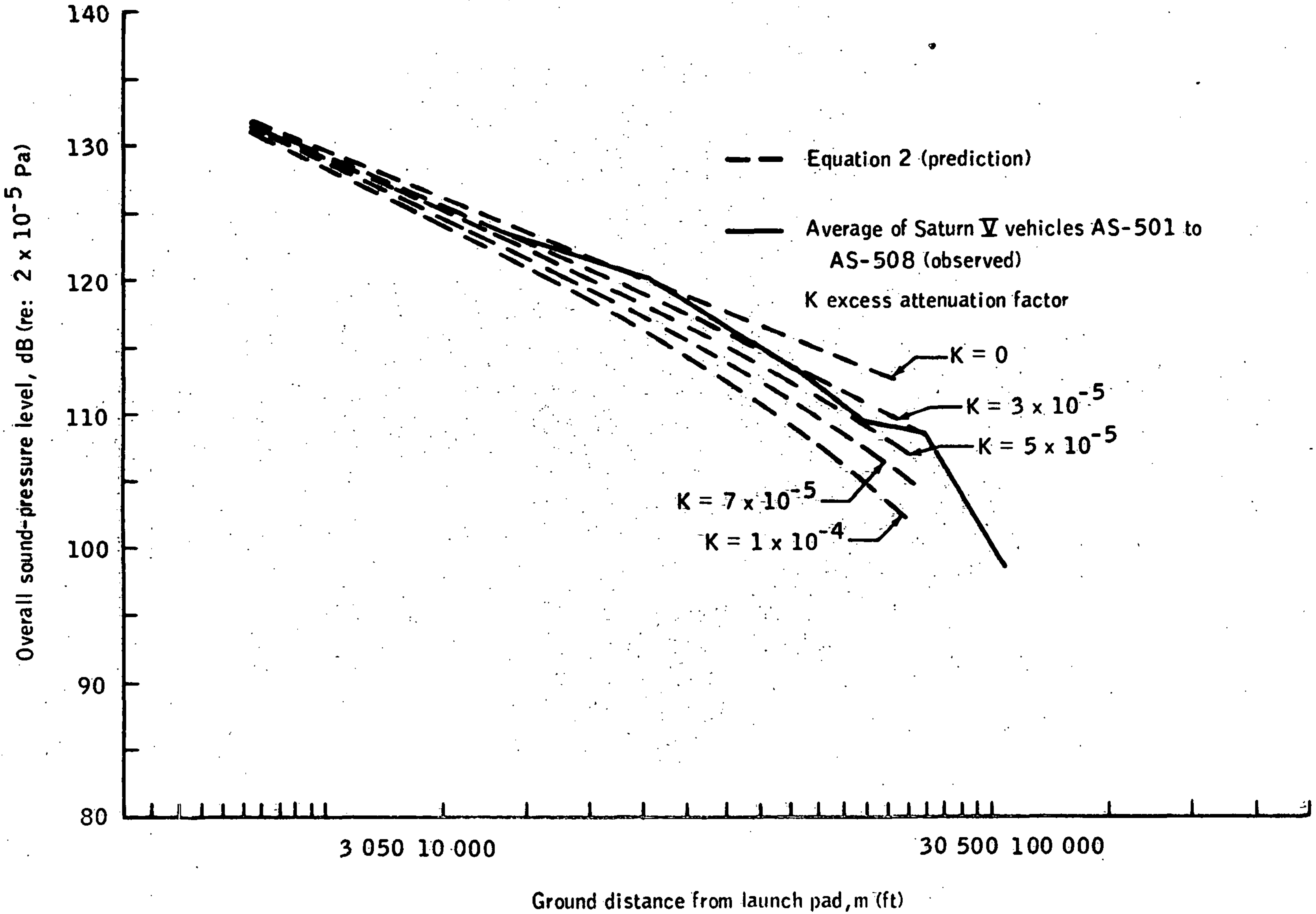


Figure 9-3.- Comparison of average Saturn V acoustic observations with prediction using equation 2 (ref. 9-1).

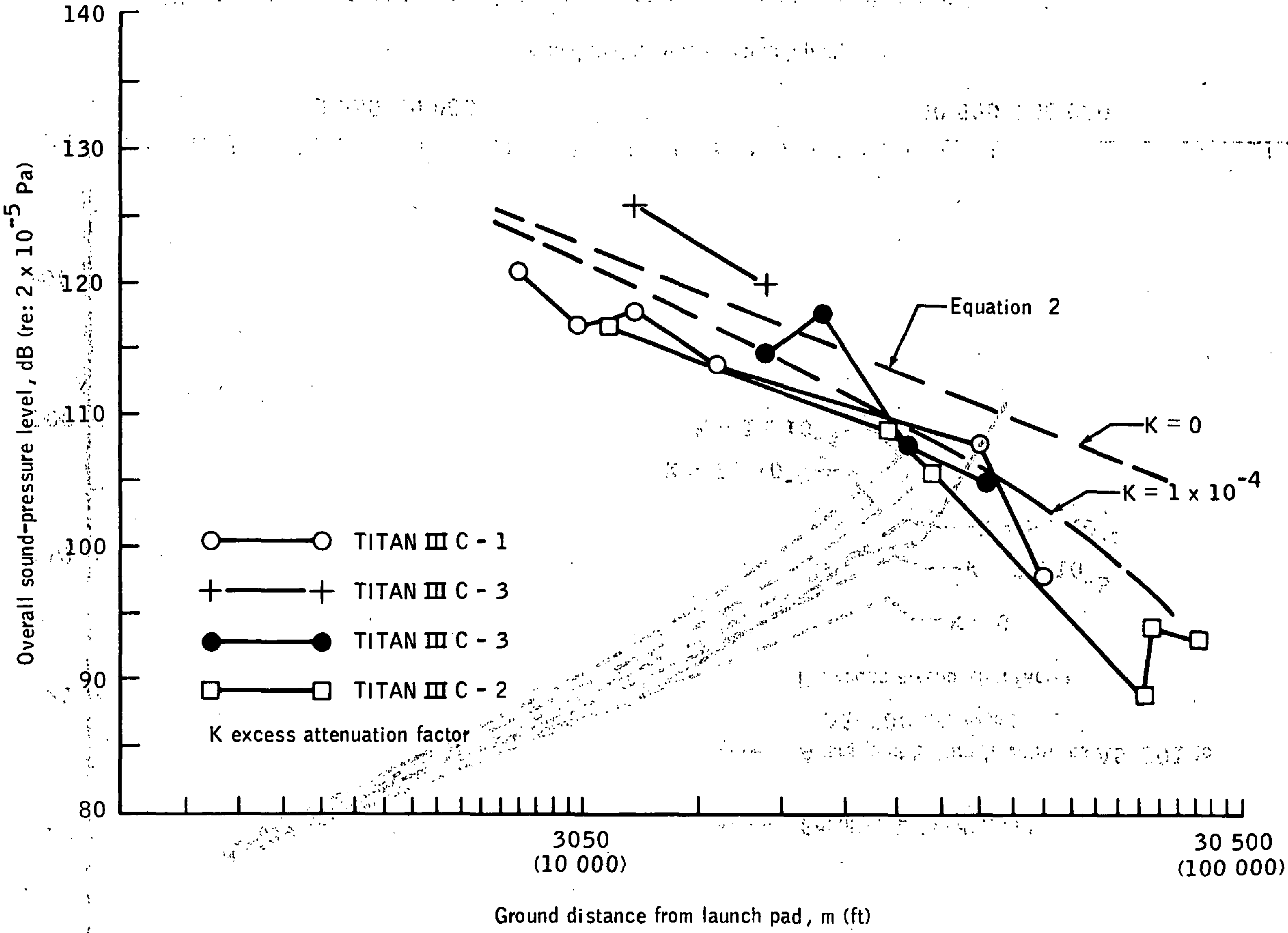


Figure 9-4.- Comparison of Titan III C acoustic observations (KSC) with predictions using equation 2 (ref. 9-1).

10. EXPOSURE LIMIT GUIDELINES

CONCERNS

Ground Cloud

The four major areas of concern with respect to the ground cloud that is formed by the Space Shuttle solid rocket boosters and drifts with the prevailing wind are as follows.

1. The toxic gases and dust may adversely affect personnel, wildlife, or vegetation on the surface below the cloud. Pilots flying small aircraft through the cloud may also be adversely affected.

2. Rainfall through the cloud or induced in the cloud will be acidic because of dissolved hydrogen chloride (HCl). If the acidity is sufficiently high, damage to plants or soil could result.

3. The aluminum oxide (Al_2O_3) dust could act as an agent for weather modification by screening sunlight or by acting as a nucleating agent for water or raindrops.

4. The cumulative effect of many launches over a period of several years could result in ecological or public health changes that cannot be predicted from the effects of a few launches in a short time.

The approach used is to define the allowable limits for the environmental effect of the cloud constituents by the use of established standards, by research, and by comparison of the baseline ecology established before the first Shuttle flight test with the ecology after Shuttle operations are well underway.

Other Toxic Substances Associated With Shuttle Operations

In addition to the ground-cloud toxicants from the solid rocket boosters, there is concern about other fuels used for the control engines of the Orbiter. The concern with these fuels is that they could affect personnel in the event of spills and in venting during loading.

Sonic Boom and Launch Noise

The concern with the overpressures connected with the sonic boom, primarily during Orbiter entry, and with the noise during launch is that they will cause physiological discomfort to the public or wildlife and/or structural damage to personal property. These effects, on the repetitive scale envisioned during Shuttle operations, might cause public resentment against the program that could lead to curtailment of operations.

TOXIC GASES

The possibility of release, either planned or accidental, of toxic gases from the solid-rocket-booster (SRB) exhaust effluents and from the fuels used in the Orbiter control engines necessitates the establishment of exposure limits for the protection of the general public. The current NASA position is to adopt the exposure limit guidelines recommended by the Committee on Toxicology of the National Academy of Science.[1]

The Committee on Toxicology recommended two basic categories of exposure limits for these gases and fuels: short-term public limit (STPL) and public emergency limit (PEL).

The STPL is a limit value designed to recognize a planned, relatively brief, emission of a pollutant into the atmosphere. The public should be able to tolerate relatively high levels of a pollutant if the duration is sufficiently brief and if the frequency of exposure and the nature of the pollutant are such that no additive or sensitizing effect results. Ten minutes is considered the shortest time period for which a limit can reasonably be assigned. Other critical time periods for which levels are set are 30 minutes, 1 hour, and 5 hours per day, 3 or 4 days each month.

The PEL is a limit value designed to apply to the unplanned or accidental release of a pollutant into the atmosphere, such as the escape of an effluent during an onpad conflagration. It is assumed that this would be a rare event with a low probability of occurrence. The levels recommended are believed by the committee to be realistic enough to apply in an actual emergency situation yet not so high that any irreversible or residual injury would accrue to the most probable sensitive segment of the exposed population.

The STPL and PEL values recommended by the committee for toxic gases from SRB effluents and Orbiter fuels are given in tables 10-I to 10-IX. Descriptive information on the properties, source, and principal toxic effects of each agent is given in the following section. The limits are given in terms of

---

[1]J. B. Stephens, R. C. Wands, and A. I. Goldford: Air Quality Guidelines for Short Term Exposures to Aerospace Exhaust Effluents," NASA TN, 1976 (To be published).

time-weighted average (TWA) concentrations and have ceiling limits. The TWA concentration is defined as

$$\bar{\chi} = \frac{1}{T}\int_0^T \chi(t)\,dt$$

where $\chi(t)$ is the instantaneous concentration at time t and T is the total exposure time. This is the total dosage D divided by the exposure time; i.e., $\bar{\chi} = D/T$.

The STPL and PEL are subject to a ceiling limit, which is the maximum instantaneous concentration $[\chi(t)]$ that is recommended during an exposure. The appropriate ceiling limit is the one for the total exposure time.

The following two rules should be observed in applying these guidelines. First, long averaging periods should not be used to suppress short-term TWA. These guidelines require that the TWA concentrations for all subperiods be met as well as the overall TWA. For example, if the effluent is present for 55 minutes, then the 1-hour guideline is used. Also, there can be no 30-minute period in which the 30-minute guideline is exceeded; nor can there be a 10-minute period in which the 10-minute guideline is exceeded. Secondly, the total exposure time determines the ceiling limit. In the previously mentioned example, the 1-hour ceiling limit is used even for periods of less than 10 minutes.

Exposure Guidelines

Hydrogen chloride.- Hydrogen chloride (HCl) is a colorless, strong-smelling gas with a molecular weight of 36.457, which is quite hygroscopic. Because of its high solubility in water, it readily forms aqueous hydrochloric acid. Under normal atmospheric conditions, it tends to form an aerosol. The odor threshold is approximately 1 to 5 p/m. At normal temperature and pressure (NTP), 1.49 mg/m^3 is equivalent to 1 p/m.

Aerospace sources: Hydrogen chloride is one of the effluents from solid rocket motors that use ammonium perchlorate as an oxidizer. All NASA SRB's currently use ammonium perchlorates in the propellant mixture.

Toxic effects: Hydrogen chloride is an irritant to the mucous membranes of the eyes and respiratory tract. A concentration of 35 p/m causes irritation of the throat after short exposure. Concentrations of 50 to 100 p/m are tolerable for 1 hour. More severe exposures result in pulmonary edema and often laryngeal spasm. Concentrations of 1000 to 2000 p/m are dangerous even for brief exposures. The STPL and PEL of hydrogen chloride are shown in table 10-I.

Carbon monoxide.- Carbon monoxide (CO) is a colorless, odorless gas with a molecular weight of 28.011. It is produced by the incomplete combustion of carbon. At NTP, 1.15 mg/m^3 is equivalent to 1 p/m.

Aerospace source: Carbon monoxide is one of the effluents from solid rocket motors that have a carbonaceous-based binder and from all liquid rocket engines that use a hydrogen carbon fuel. Most of the carbon monoxide is converted to carbon dioxide, a harmless gas, when the exhaust effluent mixes with the ambient air and afterburns.

Toxic effect: Carbon monoxide has an affinity for hemoglobin that is 200 to 300 times that of oxygen. When combined with hemoglobin, it forms carboxyhemoglobin, which causes the hemoglobin to be incapable of carrying oxygen to the tissues. Its effect on the body is therefore predominantly one of asphyxia. A concentration of 400 to 500 p/m of carbon monoxide in the air can be breathed for 1 hour (10-percent carboxyhemoglobin) without any appreciable effect. One hour of exposure to 600 to 700 p/m (15- to 18-percent carboxyhemoglobin) will cause barely appreciable effects, such as tightness across the forehead, slight headache, and dilation of cutaneous blood vessels. Carboxyhemoglobin concentrations of 20 to 30 percent cause shortness of breath and headache, and concentrations of 30 to 50 percent cause severe headache, mental confusion, dizziness, impairment of vision and hearing, and collapse upon exertion. Unconsciousness occurs with a concentration of 50- to 60-percent carboxyhemoglobin, and death may follow. The STPL and PEL of carbon monoxide are shown in table 10-II.

Hydrogen fluoride.- Hydrogen fluoride (HF) below 292 K (19° C) is a nearly colorless, corrosive liquid. At temperatures above 292 K (19° C), it exists as a gas. It has a nominal molecular weight of 20.006, but at ambient pressure and temperatures below 373 K (100° C), it exists as an associated molecule up to H_6F_6 with an average molecular weight of 50 to 55. When the anhydrous liquid HF is vaporized into the air, it forms an aerosol with the atmospheric moisture.

Aerospace source: Hydrogen fluoride is an effluent from some rocket engines that use hydrogen and fluorine as propellants.

Toxic effect: Hydrogen fluoride is extremely irritating and corrosive to the skin and mucous membranes. Inhalation of the vapor may cause ulcers of the upper respiratory tract. The highest concentration that can be tolerated for 1 minute is 120 p/m. This causes a definite smarting of the skin, a definite sour taste, and some degree of conjunctivitis and respiratory irritation. Even short exposures to concentrations of 50 to 250 p/m are considered dangerous. The STPL and PEL of hydrogen fluoride are shown in table 10-III.

Nitrogen oxides.- There are three nitrogen oxides of possible interest for air pollution purposes: nitric oxide (NO), nitrogen dioxide (NO_2), and nitrogen pentoxide (N_2O_5). Nitric oxide is of little concern as an air pollutant because it is not an irritant, has only one-fiftieth the toxicity of NO_2, and in the air is converted to NO_2. Nitric oxide is a colorless gas, and nitrogen dioxide is a brownish gas. The molecular weight of NO is 30.01; of NO_2, 46.01; and N_2O_5, 108.01.

Aerospace source: The oxides of nitrogen, in particular NO_2, are used as either direct oxidizers or as additives to oxidizers in liquid rocket engines. The brown gaseous cloud noticed during the startup sequence of the Titan II was NO_2.

Toxic effects: The oxides of nitrogen are somewhat soluble in water, reacting with it to form nitric and nitrous acids. This action takes place deep in the respiratory system. The acids that are formed cause congestion of the throat and bronchi and edema of the lungs. They are neutralized by the alkalis present in the tissues, with the formation of nitrates and nitrites. The latter may cause some arterial dilation, a fall in blood pressure, headache, and dizziness.

Because of their relatively low solubility in water, the oxides of nitrogen are only slightly irritating to the mucous membranes of the upper respiratory tract. Their warning power is therefore low, and dangerous amounts of the gases may be breathed before any real discomfort is noticed. Concentrations of 100 to 150 p/m are considered dangerous for short exposures of 30 to 60 minutes. The STPL and PEL of nitrogen oxides are shown in table 10-IV.

<u>Chlorine</u>.- Chlorine (Cl) is a greenish-yellow gas with a molecular weight of 70.91 that is only slightly soluble in water. The odor threshold of chlorine is 0.3 to 5 p/m. At NTP, 5 mg/m^3 is equivalent to 1 p/m.

Aerospace source: Although chlorine is widely used in the chemical industry, its usage in the aerospace industry is minimal. It has been reported that afterburning of the solid rocket motor exhaust effluents may change some of the HCl to chlorine.

Toxic effects: Chlorine is extremely irritating to the mucous membranes of the eyes and respiratory tract. It combines with moisture to liberate nascent oxygen and form hydrochloric acid. Both these substances can cause inflammation of the tissues with which they come in contact. If the lung tissues are attacked, pulmonary edema may result. Concentrations of 15 p/m cause immediate irritation of the throat, and concentrations of 50 p/m are considered dangerous for even short exposures. The STPL and PEL of chlorine are shown in table 10-V.

<u>Hydrazine</u>.- Hydrazine is a colorless, oily, hydroscopic, fuming-in-air liquid with an ammonialike odor and a molecular weight of 32.046. It is extremely irritating and has great reactivity with a wide variety of materials.

Aerospace source: Hydrazine is used either alone as a monopropellant or as an ingredient in liquid rocket engine fuel mixtures.

Toxic effects: In general, hydrazine and its methylated derivatives, monomethylhydrazine and unsymmetrical dimethylhydrazine, are respiratory irritants and convulsants. Exposure to hydrazine vapor produces immediate and violent irritation of the nose and throat; over a period of hours, itching, burning, and swelling of the eyes may develop. After severe exposure, nausea, dizziness, blindness which lasts for about a day, tremors, seizures, and unconsciousness may occur. The STPL and PEL of hydrazine are shown in table 10-VI.

Monomethylhydrazine.- Monomethylhydrazine (MMH) is a derivative of hydrazine and has many of the same characteristics; it is a fuming liquid with an ammonialike odor. The MMH is a strong reducing agent and undergoes rapid auto-oxidation in air. It has a molecular weight of 46.07 and an odor threshold of 1 to 3 p/m.

Aerospace source: The MMH is used almost exclusively as a rocket fuel. It is used primarily in reaction control systems and other small systems.

Toxic effects: Reliable data on human exposure to MMH are not available. However, eye and skin irritation after repeated exposures to this chemical have been reported. Human subjects experimentally exposed to 90 p/m MMH for 10 minutes experienced a slight moistening of the eyes and a slight tickling sensation of the nose. Hemotological changes, consisting of Heinz body formation, occurred, but this effect was slight and reversible. Animal experimentation has demonstrated that MMH has marked convulsant action and can produce hemolytic, renal, and hepatic damage. The STPL and PEL of MMH are shown in table 10-VII.

Unsymmetrical dimethylhydrazine.- Unsymmetrical dimethyhydrazine (UDMH) is a colorless, oily, hydroscopic liquid that fumes in air and has an ammonia-like odor. It has high vapor pressure; the vapor is only slowly oxidized in air. UDMH is a powerful reducing agent and reacts with a variety of reagents. It has a molecular weight of 60.10 and an odor threshold of 0.3 to 1 p/m.

Aerospace source: The UDMH is used as an ingredient of liquid rocket fuel for launch vehicles such as the Titan or as a fuel component in reaction control systems.

Toxic effects: Cases of human poisoning by UDMH have been rare. Symptoms of choking and difficulty in breathing, initially experienced by workers exposed to UDMH fumes, were followed 4 hours later by nausea and vomiting. Headache, nausea, shakiness, a burning sensation of the skin, sore throat, tightness in the chest, dyspnea, wheezing, twitching of the extremities, and clonic movements were reported in two workers who were accidentally exposed to Aerozine-50 vapors consisting of approximately 85-percent UDMH and 15-percent hydrazine. Pulmonary edema was a subsequent development in both individuals. There is evidence that after repeated exposures to UDMH, hemolysis may develop. Also, animal experimentation has demonstrated that UDMH is a convulsant and capable of producing renal and hepatic damage. The STPL and PEL of UDMH are shown in table 10-VIII.

Ammonia.- Ammonia (NH_3) is a naturally occurring, colorless gas with a molecular weight of 17.03. It has a disagreeable odor, and the odor threshold is approximately 5 p/m. At NTP, 1 p/m of NH_3 is 0.7 mg/m^3.

Aerospace source: Ammonia is one of the decomposition products of hydrazine. It also has a possible use as a liquid rocket fuel.

Toxic effects: Ammonia is irritating to the eyes and mucous membranes of the respiratory tract. Symptoms of exposure to ammonia include irritation of the eyes, conjunctivitis, swelling of eyelids, irritation of nose and throat, coughing, vomiting, and dyspnea. High concentrations, in addition to their corrosive action on mucous surfaces, which can cause permanent injury to the cornea, extensive damage to the throat and upper respiratory tract, and pulmonary edema, may affect heart action or cause cessation of respiration by reflex action. Irritation to the mucous membranes becomes noticeable at approximately 100 p/m. Concentrations of 2500 p/m are considered dangerous for exposures of as little as 30 minutes. The STPL and PEL of ammonia are shown in table 10-IX.

Real Case Effects

The Langley Research Center (LaRC) has monitored seven Titan launches, and the measurement teams have experienced various levels of exposure to Shuttle SRB exhaust products. They have also monitored the exhaust from the incinerator ship Vulcanus in the Gulf of Mexico at the request of the Environmental Protection Agency (EPA). The ship was incinerating petrochemical industrial waste products, and the exhaust contained HCl. The LaRC experiences with HCl indicate that the odor threshold is approximately 0.05 p/m, a concentration of approximately 1 p/m causes objectionable eye-skin irritation, and a concentration of 7 p/m causes major difficulty in breathing, eye irritation, and skin irritation.

It is not clear at this time whether the odor threshold reported for HCl is actually for HCl or whether it is really for chlorine or hypochlorous acid (HOCl). Verbal comments likening the odor to Clorox indicate that it is chlorine or hypochlorous acid. This is not the case with the reports of the experiences at 7 p/m in the exhaust from the Vulcanus, where HCl was the basic constituent.

ALUMINUM OXIDE

The exposure limits adopted by NASA comply with the EPA National Primary and Secondary Ambient Air-Quality Standards for particulate matter.[2] These are as follows:

1. The national primary ambient air-quality standards define levels of air quality judged necessary to protect public health with an adequate margin of safety as follows:

   a. 75 $\mu g/m^3$ (annual geometric mean)

   b. 260 $\mu g/m^3$ (maximum 24-hour concentration not to be exceeded more than once per year)

2. The national secondary ambient air-quality standards define levels of air quality judged necessary to protect the public welfare from any known or anticipated adverse effects of a pollutant as follows:

   a. 60 $\mu g/m^3$ (annual geometric mean)

   b. 150 $\mu g/m^3$ (maximum 24-hour concentration not to be exceeded more than once per year)

3. The Florida State Pollution Control particulate allowables are as follows:

   a. 50 $\mu g/m^3$ (maximum annual geometric mean)

   b. 180 $\mu g/m^3$ (maximum 24-hour arithmetic mean)

CHLORIDED ALUMINUM OXIDE

There is strong experimental evidence that some aluminum oxide particles act as nuclei for condensation of water and HCl (Cofer and Pellett; appendix E). The result is an acid particle that might be a health or nuisance problem and might be cosmetically harmful to plants, fruits, and vegetables.

The allowables for chlorided aluminum oxide have not been established as yet. However, NASA intends to conduct a survey of industrial organizations familiar with the use of chlorided aluminum oxide (deodorants, etc.) and to attempt to establish guidelines from both the public health and ecological standpoints. It should be noted that there are a large number of chloride ions in human and plant tissue and it is not these ions that are toxic; it is the acidity.

---

[2] Code of Federal Regulations, title 40, part 50, July 1975.

ACIDIC RAINFALL

No standards for acidic rainfall are available at this time. However, the soils in the KSC area have a natural buffering capacity that tends to obviate part or all of the acidic rainfall effects.

SONIC BOOM

Exposure guidelines for sonic boom overpressures have not been addressed by any regulatory agency. However, the 1972 Environmental Statement for the Space Shuttle Program quotes the summation of the work done[3] on the effects of sonic booms as a guide to requirements for Shuttle operations. This guide is reproduced here for convenience as follows.

1. The probability of immediate direct injury to persons exposed to sonic boom is essentially zero.

2. The percentage of persons queried who rated sonic booms occurring 10 to 15 times daily as annoying increased with increasing overpressures. For overpressures less than about 24 pascals (0.5 psf), no one rated the boom as annoying; approximately 10 percent considered a 48-pascal (1 psf) sonic boom annoying and nearly all considered 144-pascal (3 psf) booms annoying (fig. 10-1).

3. Primary (loadbearing) structures that met acceptable construction standards or were in good repair showed no damage from overpressures as high as approximately 950 pascals (20 psf). Nonprimary structures such as plaster, windows, and bric-a-brac sustained some damage from overpressures as high as 48 to 144 pascals (1 to 3 psf).

4. Ground motions from sonic booms were found to be of the magnitude caused by footsteps.

The annoyance criteria are conservative in view of the expected low frequency of Shuttle flights of approximately one per week.

The threshold limiting value currently used as a criterion is 96 pascals (2.0 psf) and is based on the fact that this level was accepted for the 1972 Environmental Statement. At this level, according to the International Civil Aviation Organization (ICAO) Summary, the effects are (1) annoyance of 30 to 40 percent of the affected population and (2) possible damage to nonprimary structures such as plaster, windows, and personal bric-a-brac.

---

[3] Report of the Sonic Boom Panel, International Civil Aviation Organization, Oct. 1970.

LAUNCH NOISE

Exposure guidelines to low-frequency sound (<100 hertz), such as expected from Shuttle lift-off, have not been adopted by the EPA or other agencies because such noise is uncommon in daily experience. Any standards adopted for sound higher than 100 hertz are not appropriate for Shuttle (ref. 10-1).

In the absence of any new criteria, the statements contained in the 1972 Environmental Statement for the Space Shuttle Program are reproduced here for convenience.

"There is a general lack of information on the effects of noise (including sonic boom which is discussed in the next section) on wildlife. It is evident that under certain conditions there may be some ecological effects, particularly when new noises enter wildlife habitats. At the same time, certain species seem to show adaptation to noise. The present state of knowledge in this area is incomplete. For the Space Shuttle test and launch and landing sites where high intensity noise is generated in the proximity of the vehicle during tests and launches, some wildlife may be affected. Based on experience with rocket engine tests and space launches to date, particularly during the Apollo Program, no significant effect is foreseen."

The guidelines provided by the U.S. Air Force Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base for Shuttle operations at Vandenberg Air Force Base (ref. 10-1) are summarized in the report as follows.

"There will be no environmental impact (personal harm) from exposures of uncontrolled populations to infrasound at discrete frequency and octave band levels below 120 decibels re 2×10^{-5} pascals. This 120-decibel level includes approximately a 10-decibel margin of safety; thus, undue caution is not required in its application as a boundary."

Environmental Effects in Controlled Areas

Damage risk criteria for personnel in controlled areas are presented in table 10-X. These criteria concern the physiological damage (i.e., hearing or body damage) that may result if the sound-pressure-level magnitude and duration in the indicated frequency range are exceeded. The criteria are considered valid for personnel with no protection for a single daily exposure. Space Shuttle operational personnel within this area will be protected so that these limits will not be exceeded. Throughout the Apollo-Saturn V program, which generated frequencies and intensities of the same order as the Space Shuttle will, operational observers were stationed 3500 meters (11 500 feet) from the launch pad in a small enclosure, and emergency crews were located approximately 550 meters (1800 feet) from the launch site in standard armored personnel carriers. None of these personnel sustained injury.

Structural damage is possible with low-frequency, high-intensity noise. Therefore, structures within the controlled area will be designed to withstand the noise environment to which they are to be exposed.

Environmental Effects in Uncontrolled Areas

For uncontrolled areas, a general noise exposure criterion of a maximum overall sound-pressure level of 115 decibels re 0.00002 pascals for both man and structures has been established by the Launch and Landing Site Review Board. Normally, the acoustic energy which propagates into this region is of low frequency (i.e., 100 hertz and below). For acoustic energy in this frequency range, the 115-decibel OASPL[4] criterion is considered acceptable and has been substantiated by personnel and community noise exposure experienced during Saturn IB and Saturn V launches and by analysis of structural damage from low-frequency noise.

FUTURE WORK

There is a continuing effort to obtain exposure limits for those areas identified in this section as having either nonexistent or deficient limits. Specifically, these include the combined effects of hydrogen chloride and aluminum oxide (i.e., chlorided Al_2O_3) on public health and plants, acidic rainfall effects on plantlife (short term and long term) and on the ecosystem (long term), and the establishment of an ecological and acidic rainfall pre-Shuttle baseline.

CONCLUSIONS

The guidelines suggested by the Committee on Toxicology of the National Academy of Science for toxic gases present in the Shuttle SRB exhaust or associated with the Shuttle are adequate for the Shuttle environmental effects assessment. In addition, the EPA National Primary and Secondary Air Quality Standards for particulates, the ICAO sonic boom effects criteria, and the launch noise criteria of the 1972 Environmental Statement are acceptable guidelines for NASA in these areas.

The limits for the combination of hydrogen chloride and aluminum oxide and acidic rainfall are not available but are being actively sought. Also, an ecological baseline is being established to determine long-range Shuttle environmental effects.

---

[4] Octave A-weighted band sound pressure level.

REFERENCE

10-1. Smith, J. R.: Effects of Shuttle Noise and Exhaust Products Dispersion on Launch Site Selection at Vandenberg Air Force Base. Report No. TOR-0075 (5421-04)-9, Aerospace Corp. (El Segundo, Calif.), Mar. 31, 1975.

TABLE 10-I.- EXPOSURE GUIDELINES FOR HYDROGEN CHLORIDE

Exposure time	TWA concentration, p/m	Ceiling limit, p/m
	STPL	
10 min	4	8
30 min	2	4
60 min	2	4
1 hr/day	2	4
5 hr/day, 3 to 4 days/month	.7	--
	PEL	
10 min	7	14
30 min	3	6
60 min	3	6

TABLE 10-II.- EXPOSURE GUIDELINES FOR CARBON MONOXIDE

Exposure time	TWA concentration, p/m	Ceiling limit, p/m
	STPL	
10 min	90	135
30 min	35	53
60 min	25	38
4 to 5 hr/day, 3 to 4 days/month	15	--
	PEL	
10 min	275	275
30 min	100	100
60 min	60	60

TABLE 10-III.- EXPOSURE GUIDELINES FOR HYDROGEN FLUORIDE

Exposure time	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10 min (limit 1 hr/day)	4	10
30 min (limit 1 hr/day)	4	5
60 min (limit 1 hr/day)	4	5
5 hr/day, 3 to 4 days/month	1	--
PEL		
10 min	10	10
30 min	5	5
60 min	5	5

TABLE 10-IV.- EXPOSURE GUIDELINES FOR NITROGEN OXIDES

Exposure time	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10 min	1	1
30 min	1	1
60 min	1	1
5 hr/day, 3 to 4 days/month	.5	--
1 hr/day/year	1	--
PEL		
10 min	5	5
30 min	3	3
60 min	2	2

TABLE 10-V.- EXPOSURE GUIDELINES FOR CHLORINE

Exposure time, min	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10	1	3
30	.5	1
60	.5	1
PEL		
10	3	3
30	2	2
60	2	2

TABLE 10-VI.- EXPOSURE GUIDELINES FOR HYDRAZINE

Exposure time, min	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10	15	30
30	10	20
60	5	10
PEL		
10	30	30
30	20	20
60	10	10

TABLE 10-VII.- EXPOSURE GUIDELINES FOR MONOMETHYLYHYDRAZINE

Exposure time, min	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10	9	90
30	3	30
60	1.5	15
PEL		
10	90	90
30	30	30
60	15	15

TABLE 10-VIII.- EXPOSURE GUIDELINES FOR 1-DIMETHYLHYDRAZINE

Exposure time, min	TWA concentration, p/m	Ceiling limit, p/m
STPL		
10	50	100
30	25	50
60	15	30
PEL		
10	100	100
30	50	50
60	30	30

TABLE 10-IX.- EXPOSURE GUIDELINES FOR AMMONIA

Exposure time	TWA concentration, p/m	Ceiling limits, p/m
STPL		
10 min	20	20
30 min	10	10
60 min	10	10
5 hr/day, 3 to 4 days/month	5	5
PEL		
10 min	100	100
30 min	75	75
60 min	50	50

TABLE 10-X.- DAMAGE RISK CRITERIA[a] FOR CONTROLLED AREAS

[Physiological damage: no protection, single daily exposure]

Frequency range, Hz	Duration, min	Sound-pressure level, dB re 0.00002 Pa
1 to 20	--	(b)
20 to 100	20	135
100 to 6300	8	125 dBA[c]

[a]Level and duration not to be exceeded or damage will result.

[b]No criteria have been developed for this area.

[c]dBA; measured with an A-weight frequency network.

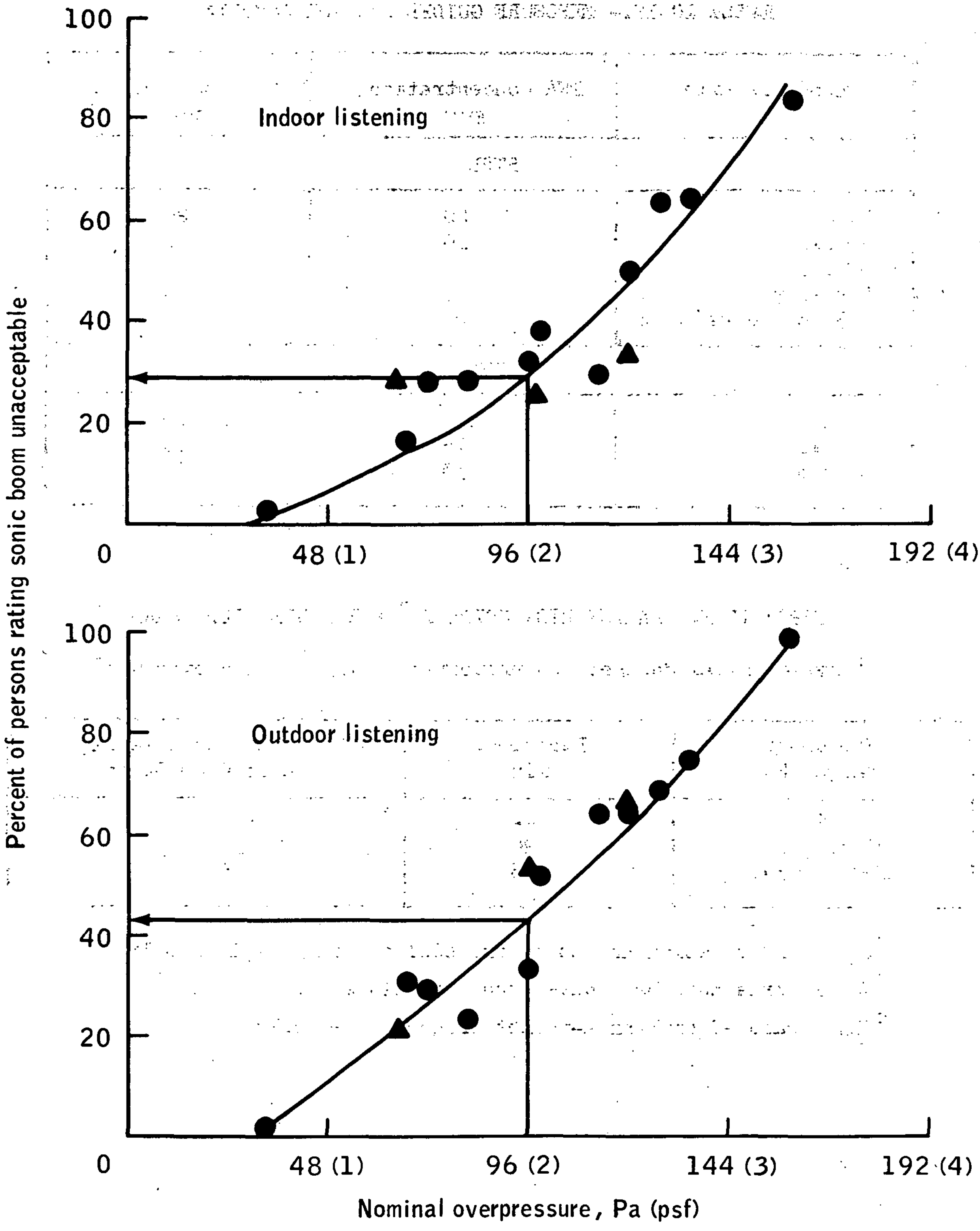


Figure 10-1.- Shuttle sonic boom annoyance.

APPENDIX A - SOURCE TERMS

This appendix includes brief descriptions of work in progress at the time of the workshop and related presentations made at the workshop. These brief descriptions include the following material.

1. "Nitric Oxide Production by Space Shuttle Solid Rocket Motors," by Richard I. Gomberg of NASA Langley Research Center (LaRC).

2. "Source Term Predictions and Measurements," excerpts of presentation by Richard I. Gomberg.

3. "Tropospheric Plume Studies," excerpts of presentation by Richard I. Gomberg.

4. "Exhaust Effluents From the Space Shuttle Solid Rocket Booster," excerpts of presentation by Arnold I. Goldford of Science Applications, Inc.

5. "Examination of Asbestos Emitted From the Space Shuttle Solid Rocket Booster," a paper prepared by the LaRC staff in response to questions that arose during the workshop.

Excerpts of the investigators' material are presented to illustrate the original concepts and to provide information that was not included in the text. As supplementary material, these excerpts should not be considered as definitive or discrete papers because much of the investigation is still preliminary and much overlapping is involved. All references, tables, and figures for the material are given at the end of this appendix.

NITRIC OXIDE PRODUCTION BY SPACE SHUTTLE SOLID ROCKET MOTORS

Troposphere

Two studies have been completed on nitric oxide (NO) production in the troposphere. The first study (ref. A-1) shows that the NO produced by a Shuttle booster is approximately twice that produced by a Titan III-C booster at altitudes less than 1 kilometer. At altitudes higher than 1 kilometer, the NO produced begins to decrease for both the Titan and Shuttle. Because of differences in the steering mechanism for the boosters, the NO production for the Shuttle decreases more quickly with altitude than the Titan until, at 10 to 15 kilometers, the Titan actually produces more NO than the Shuttle.

The second study on tropospheric NO production uses a more complete chemical scheme than the first — 36 reactions that include ozone (O_3) and chlorine monoxide (ClO), compared to 18 reactions without these species. A technique to ensure mass balance is introduced and used. This study arrives at similar conclusions regarding NO.

At altitudes below 5 kilometers, the Shuttle boosters produce approximately twice the oxides of nitrogen (NO_x) that the Titan III boosters produce (table A-1). This is quite reasonable because the two motors are similar and the mass flow of the Shuttle is approximately twice that of the Titan. This report also shows that combustion is complete and that, at high temperature, 10 percent of the gaseous chlorine takes on forms other than hydrogen chloride (HCl).

Stratosphere

Two studies have also been completed on NO production in the stratosphere. These studies were conducted by the Aero Chem Corporation. The first study (ref. A-2) shows that the preponderance of stratospheric NO production is caused by the trailing Mach disk. At 30 kilometers altitude, Shuttle boosters together deposit 4 grams of NO per meter of altitude, which represents a mass flow of less than 0.1 percent of the motor mass flow.

The second study shows that the effect of the interactions between the shock waves from the two boosters would increase the NO production by less than 10 percent, while the phenomenon of base recirculation will increase the results by less than 35 percent. This is well within the uncertainty of the calculations that include a possible error factor of 3.

SOURCE TERM PREDICTIONS AND MEASUREMENTS (PRESENTATION EXCERPTS)

The Environmental Statement for the Space Shuttle Program, 1972, uses a model to predict the percentage by weight of various chemical species in the Space Shuttle solid rocket motor (SRM) effluent. A variation of this model used by the LaRC in 1976 yields somewhat different results. The two sets of results are contrasted in table A-II.

The pad-sound-suppression scheme has also been considered in terms of effects on production of various effluents. Figure A-1 diagrams the process and shows "flow over drift" compared to time after launch. Table A-III shows the effect of varying flow rates of the acoustic damping water on certain effluents. Figure A-2 shows the difference in the SRM centerline exhaust temperature that is caused by varying flow rates of cooling water. Table A-IV shows the effects of several variations in the rate coefficient on production of certain effluents. Verification of these data has been sought through photographs, infrared radiometer measurements, and aircraft measurements.

TROSPOSPHERIC PLUME STUDIES
(PRESENTATION EXCERPTS)

Plume effects are a major factor in effluent production in the troposphere, and these effects have been studied at LaRC. Generally, exit nozzle-plane conditions have been obtained from other sources. Then, a nonequilibrium chemical, axisymmetric, turbulent mixing model is used to predict amounts of pollutants that finally reach the cool regions of the plume. The mixing model is important because a molecule undergoes "after burning" for approximately 3 seconds from the time it leaves the nozzle.

The LaRC model has been modified somewhat to match the observed data. The difference in results is shown for production of aluminum oxide (Al_2O_3) in figure A-3. The original model is shown by two formulas.

$$\frac{|T_{atm} - T_{adj}|}{|T_{atm}|} > 0.05$$

$$\frac{|U_{atm} - U_{adj}|}{|U_{atm}|} > 0.01 \qquad \text{(A-1)}$$

where T_{atm} is temperature of the (atmosphere) outermost stream tube, T_{adj} is the temperature of the adjoining (second to outermost) stream tube, U_{atm} is velocity of particles within the outermost stream tube, and U_{adj} is velocity of particles within the adjoining stream tube. Many chemical species are truncated at the atmospheric boundary in the original model. Use of the modified model starts with the original criteria, calculates mass flow of Al_2O_3 at the exit plane and every step, and lowers the value on the right-hand side of the equation if mass is lost.

Various chlorine species are displayed in figure A-4 in terms of distance downstream from the Shuttle motor. Table A-V shows the predicted abundances (in grams per meter) of certain compounds 1 kilometer downstream from the exit plane at 1 kilometer and at 18 kilometers.

In conclusion, the low altitude plume program (LAPP) can be used to study "after burning" far downstream from the exit plane. From this model, a detailed chemical analysis of the plume is obtained, and this analysis is useful for environmental studies.

EXHAUST EFFLUENTS FROM THE SPACE SHUTTLE SOLID ROCKET BOOSTER (PRESENTATION EXCERPTS)

A direct approach to the study of Shuttle effluents begins with the chemical composition of the propellant (table A-VI). Observed exhaust composition is shown in table A-VII. Reactions that may be involved with "after burning" are shown in table A-VIII. Finally, table A-IX gives a comparison between the Shuttle and several other rocket motors in terms of mass of propellant expended per second and energy produced per second.

EXAMINATION OF ASBESTOS EMITTED FROM THE SPACE SHUTTLE SOLID ROCKET BOOSTER

As a result of discussions at the Space Shuttle Environmental Assessment Workshop (Troposphere), a cursory analysis of the total amount of inert materials consumed by the Shuttle solid rocket boosters (SRB's) was made to determine how much asbestos would be deposited in the troposphere. The total inert material consumed by one Shuttle SRB was obtained from Thiokol nominal data for the John F. Kennedy Space Center (KSC) conditions; the information is as follows:

SRB component	Inert material expended, kg (lb)	Asbestos, percent
Insulation	2269 (5 000)	28
Inhibitor	418 (922)	?
Liner	679 (1 496)	10
Nozzle	1684 (3 713)	?
Total	5050 (11 134)	

Since the percent asbestos for each compartment could not be determined, a 30-percent asbestos content was applied to the total inert material to estimate the amount of asbestos emitted over the total burntime. Thus, 1515 kilograms (3340 pounds) of asbestos would be consumed during total burntime (5050 kilograms (11 134 pounds) times 0.30 is equal to 1515 kilograms (3340 pounds)).

To determine the amount emitted in the lower troposphere that would be diffused to the ground level in the vicinity of the launch site, it was assumed that only the first 20 seconds of burning contribute to this lower altitude area. This gives 253 kilograms (557 pounds) of asbestos emitted into the lower troposphere by one SRB (20/120 times 1515 kilograms (3340 pounds) is equal to 253 kilograms (557 pounds)). The total tropospheric emission for two SRB's is then 1114 pounds or approximately 510 kilograms.

Assume a cloud volume of 6 to 8 km^3 to obtain the in-cloud concentration of the asbestos in the stabilized tropospheric ground cloud. This gives the in-cloud asbestos concentration as 64 to 85 $\mu g/m^3$; i.e., 510 kilograms divided by 6 and 8 km^3.

Now assume that a 10^2 reduction is the rule for calculating ground-level concentrations when given in cloud data, then ground-level asbestos concentration is 0.64 to 0.85 $\mu g/m^3$.

The 8-hour air quality standard effective after July 1, 1976, for asbestos is 2 fibers/cm^3 (ref. A-3); where each fiber has a length greater than 5 micrometers and a length to diameter ratio greater than 3. By using the density of fibrous serpentine (i.e., chrysotile, $3M_gO.2SiO_2.2H_2O$) as 2.5, then the standard can be converted to an allowable concentration of 55 $\mu g/m^3$.

As can be seen from these simple calculations, neglecting the destruction of the asbestos fibers in the SRB combustion processes, the expected in-cloud concentrations are approximately equal to the standard and are most likely much less if an accurate inventory of the asbestos in the inhibitor and nozzle inert weight were available. However, since the melting temperature of the asbestos, 1973 to 2073 K (1700° to 1800° C), is much lower than the chamber temperatures and the plume temperatures of 2773 K (2500° C), the asbestos will be fused in the internal and external combustion processes. As a result no asbestos fibers will be present in the exhaust gases. Until a more detailed study can be made, it can be tentatively concluded that there is not an air quality problem resulting from the asbestos used in the Shuttle SRB's.

REFERENCES

A-1. Simpson, Janet P.: Infrared Emission From the Atmosphere Above 200 km. NASA TN D-8138, 1976.

A-2. Pergament, Harold S.; and Thorpe, Roger D.: NO_x Deposited in the Stratosphere by the Space Shuttle, Phase 1. Final Summary Report. NASA CR-132715, 1975.

A-3. Federal Register, vol. 39, no. 125, June 27, 1974.

TABLE A-I.- OXIDES OF NITROGEN PRODUCTION

Altitude, km	NO_x production, g/m	
	Shuttle	Titan III
0.7	967	496
5	108	--
10	24	--
15	6	--
18	--	22

TABLE A-II.- PREDICTED SPACE SHUTTLE EFFLUENTS

Species	Predicted value, wt%	
	Space Shuttle Environmental Statement, 1972	1976 Langley version (less entrained air)
HCl	20.9	15.4
Cl_2	.06	1.7
CO	24.37	.05
N_2	8.5	--
H_2O	10.39	23.3
H_2	2.11	0
CO_2	4.32	33.6
NO	—	1.1
OH	.01	0
H	.01	0
Al_2O_3	28.3	24.6
$AlCl_x$	.02	--
$FeCl_x$	.1	--

TABLE A-III.- EFFECT OF WATER ON EXHAUST COMPOSITION AT ALTITUDE OF 1 KILOMETER

[Rate coefficient:[a] $1 \times 10^{-16} T$
(Mass flow: 4.4×10^{6} g·sec^{-1}/motor)]

Species	Deposition, g/m		
	H_2O flow = 0.25 exhaust flow	H_2O flow = 1 × exhaust flow	H_2O flow = 2 × exhaust flow
HCl	17 124	17 773	18 400
Cl_2	2 151	1 599	782
NO	1 444	503	16
CO	55	77.9	288
CO_2	37 896	37 828	37 157

[a]Where T = temperature.

TABLE A-IV.- PARAMETRIC STUDY OF RATE COEFFICIENT[a]

Species	Effluent production, g/m, at -		
	$10^{-17}\sqrt{T}$	$10^{-16}\sqrt{T}$	$10^{-15}\sqrt{T}$
CO	242	288	1 844
NO	13	16	2
CO_2	37 790	37 157	34 326
HCl	18 288	18 400	18 961
Cl_2	811	782	2.6

[a]Notes:

$$\frac{dm_{H_2O}}{dt} = 2 \times \frac{dm_{SRB}}{dt} \quad \text{and} \quad \frac{dm_{SRB}}{dt} = 4.4 \times 10^{6} \text{ g/sec-motor}$$

where m is mass in grams, t is time in seconds, and T is temperature in Kelvin.

TABLE A-V.- ABUNDANCE OF CERTAIN SPECIES 1000 METERS DOWNSTREAM OF THE EXIT PLANE

Species	For Titan III, g/m, at vehicle altitude of -		For Shuttle, g/m, at vehicle altitude of -			
	1 km	18 km	1 km	5 km	10 km	15 km
HCl	7 565	354	13 708	1992	1420	1099
Cl_2	833	58.6	1 543	240	210	213
ClO	.05	.057	.5	.070	.04	.16
Cl	16.7	62.3	21.6	14	30	95.8
NO	489	16.7	954	107	28	5.7
NO_2	6.3	.091	12.9	1.5	.4	.13
CO	38.3	13.7	50	17	25	37.6
CO_2	17 698	921	29 828	4372	3274	2705
Al_2O_3	11 194	593	21 807	3205	2418	2018
H_2	.006	.004	.02	.002	.006	.005
H_2O	11 791	636	20 713	3055	2320	1959
O	.0003	.074	.0002	.0005	.005	.12
OH	.003	.055	.004	.002	.008	.11
N_2	12.7×10^6	0.36×10^6	23.2×10^6	2.1×10^6	1.2×10^6	1.0×10^6
O_2	3.4×10^6	0.09×10^6 (still reacting)	6.2×10^6	0.57×10^6	0.34×10^6	0.28×10^6 (still reacting)

TABLE A-VI.- PROPELLANT COMPOSITION

Constituent	Amount, wt%
Aluminum (Al)	16.0
Ammonium perchlorate (NH_4ClO_4)	69.6
Iron oxide (Fe_2O_3)	.4
Binder 1 ($C_{6.884}H_{10.089}N_{0.264}O_{0.278}$)	12.04
Binder 2 ($C_{6.15}H_{6.97}N_{0.03}O_{1.17}$)	1.96

TABLE A-VII.- EXHAUST COMPOSITION

[1-D thermochemical equilibrium[a]
$P_c = 5.378 \times 10^6$ N/m^2 (780 psia)]

Compound	Mole fraction	Compound	Mole fraction
$Al_2O_{3(s)}$	0.07980	H_2	0.27912
CO	.23255	H_2O	.13909
CO_2	.02092	N_2	.04808
Cl	.00185	OH	.00037
H	.00455	NO	.00001
HCl	.15754	$FeCl_x$	.00012

[a]Where P_c is chamber pressure and 1-D indicates one dimensional.

TABLE A-VIII.- "AFTER BURN" ANALYSIS

Reactions being considered	Reactions being considered
$HCl + OH = H_2O + Cl$	$H + HO_2 = OH + OH$
$H + HCl = Cl + H_2$	$H + O_2 + M = HO_2 + M$
$OH + Cl = HCl + O$	$O + H_2 = OH + H$
$Cl + HO_2 = HO_2 + O_2$	$O + HO_2 = OH + O_2$
$ClO + OH = HO_2 + Cl$	$OH + HO_2 = O_2 + H_2O$
$H + Cl_2 = HCl + Cl$	$H_2 + HO_2 = H_2O + OH$
$O + HCl = Cl + OH$	$H + OH + M = H_2O + M$
$Cl + O_3 = ClO + O_2$	$H + HO_2 = H_2 + O_2$
$Cl + Cl + M = Cl_2 + M$	$OH + H_2 = H_2O + H$
$O + Cl + M = ClO + M$	$N + O_2 = NO + O$
$ClO + H = HCl + O$	$NO + O + M = NO_2 + M$
$O + ClO = Cl + O_2$	$NO + ClO = Cl + NO_2$
$H + Cl + M = HCl + M$	$NO + O_3 = NO_2 + O_2$
$O_3 + O = O_2 + O_2$	$NO_2 + H = NO + OH$
$O + O + M = O_2 + M$	$N + NO = N_2 + O$
$O + H + M = OH + M$	$CO + OH = CO_2 + H$
$H + H + M = H_2 + M$	$CO + O + M = CO_2 + M$
$OH + OH = H_2O + O$	$CO + HO_2 = CO_2 + OH$
$H + O_2 = OH + O$	

TABLE A-IX.- SOLID ROCKET MOTOR PARAMETERS FOR DESIGNATED VEHICLES

Vehicle	Solid motor designation	No. of motors	Total $\dot{M}$, g/sec (a)	$\dot{Q}$, J/g (cal/g) (a,b)	Total Q, J/sec (cal/sec) (a)
Space Shuttle	SRB	2	$1.376\ 593\ 6\times10^{7}$	8 889.7 (2124.7)	$1.223\ 756\ 5\times10^{11}$ ($2.924\ 848\ 4\times10^{10}$)
Thor-Delta	Castor 2	6	$7.356\ 756\times10^{5}$	10 204.8 (2439.0)	$7.507\ 404\ 7\times10^{9}$ ($1.794\ 312\ 8\times10^{9}$)
	Castor 4	5	$9.298\ 675\times10^{5}$	7 760.9 (1854.9)	$7.216\ 61\times10^{9}$ ($1.724\ 811\ 2\times10^{9}$)
Minuteman	Stage 1	1	$4.684\ 476\times10^{5}$	8 601.9 (2055.9)	$4.029\ 532\ 6\times10^{9}$ ($9.630\ 814\ 21\times10^{8}$)
Titan III	1205	2	$5.437\ 528\times10^{6}$	8 456.3 (2021.1)	$4.598\ 127\ 2\times10^{10}$ ($1.0989\ 978\ 8\times10^{10}$)

[a] Where $\dot{M}$ is mass flow of propellant, $\dot{Q}$ is effective fuel heat content, and Q is heat flow rate.

[b] These values do not include the effects of either plume mixing and "after burn" or radiation loss.

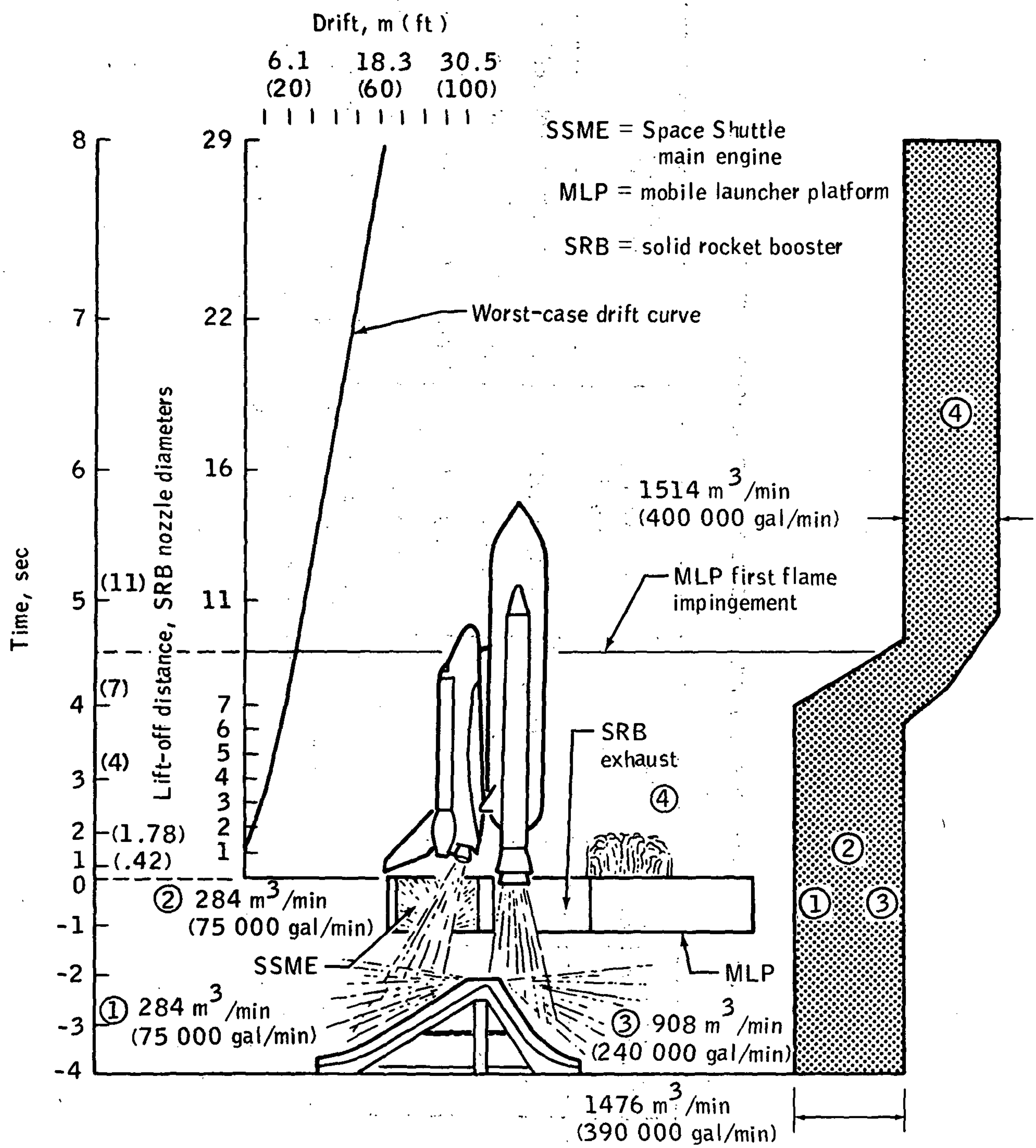


Figure A-1.- Pad-sound-suppression scheme; plot of flow/drift compared to time and mass of propellant exhausted.

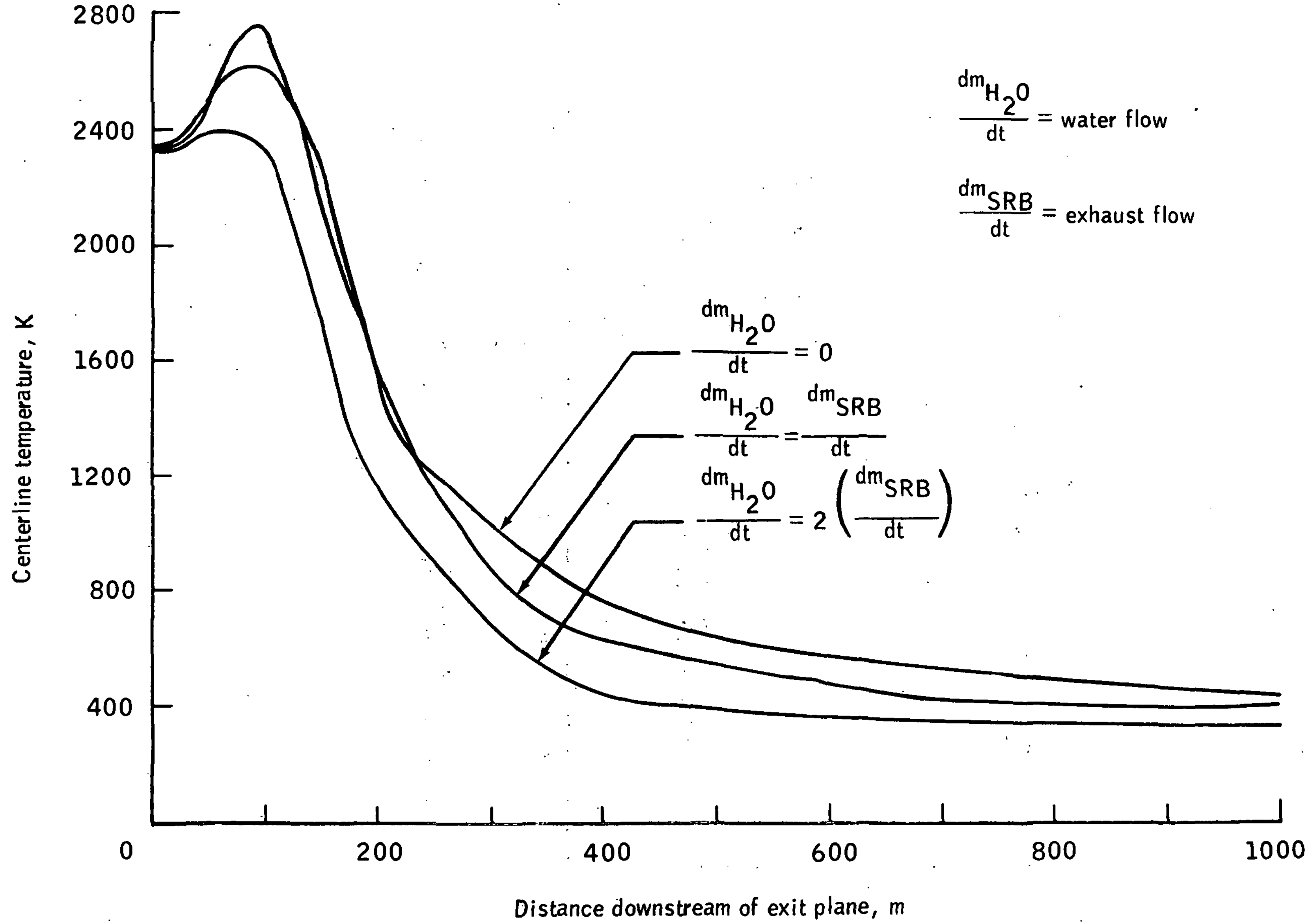


Figure A-2.- The effect of water on the center line temperature of the exhaust gases from the Space Shuttle motor at an altitude of 1 kilometer. (Rate coefficient = $10^{-16}\sqrt{T}$.)

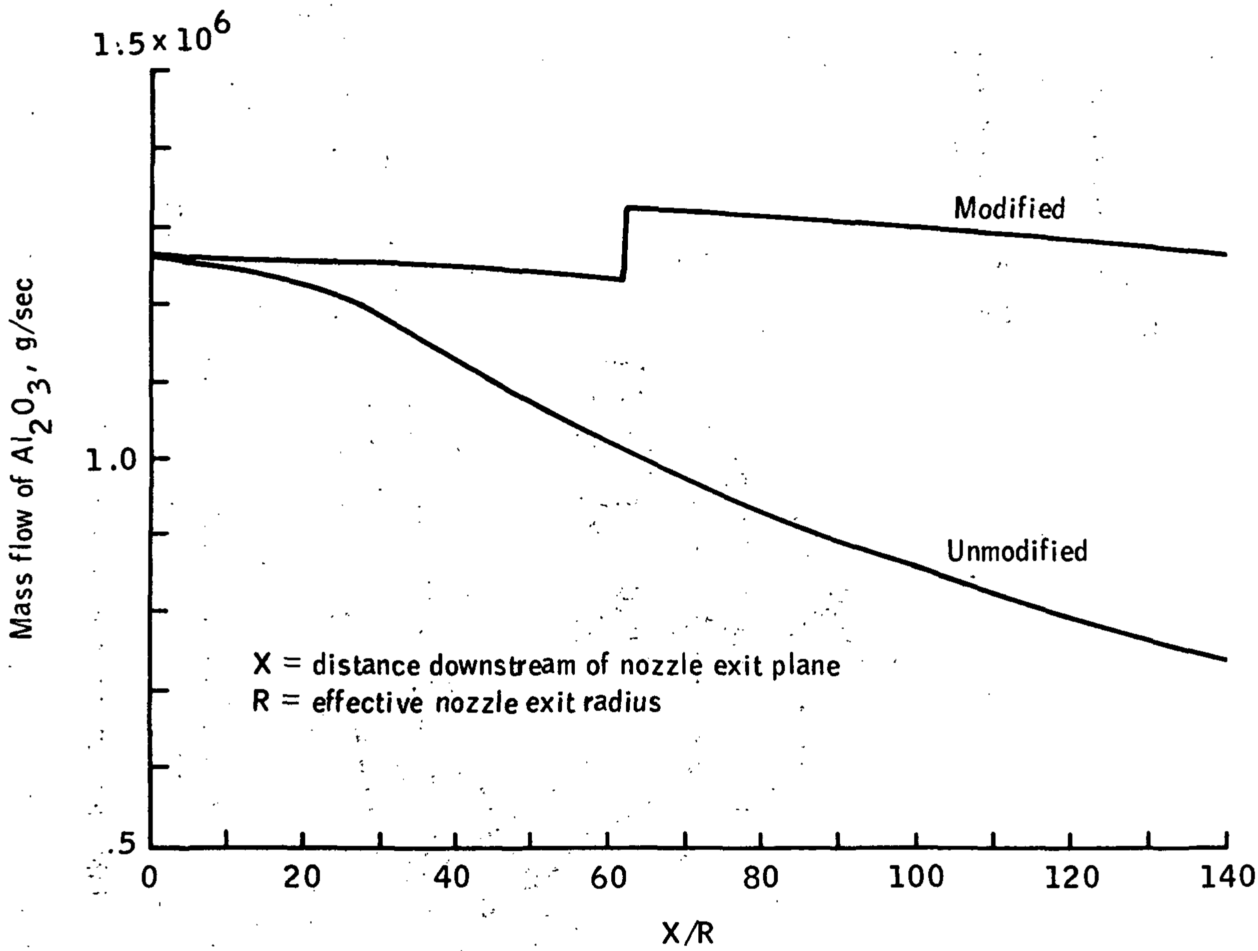


Figure A-3.- The mass flow of aluminum oxide compared to downstream distance in the plume of a Shuttle motor at 15 kilometers altitude.

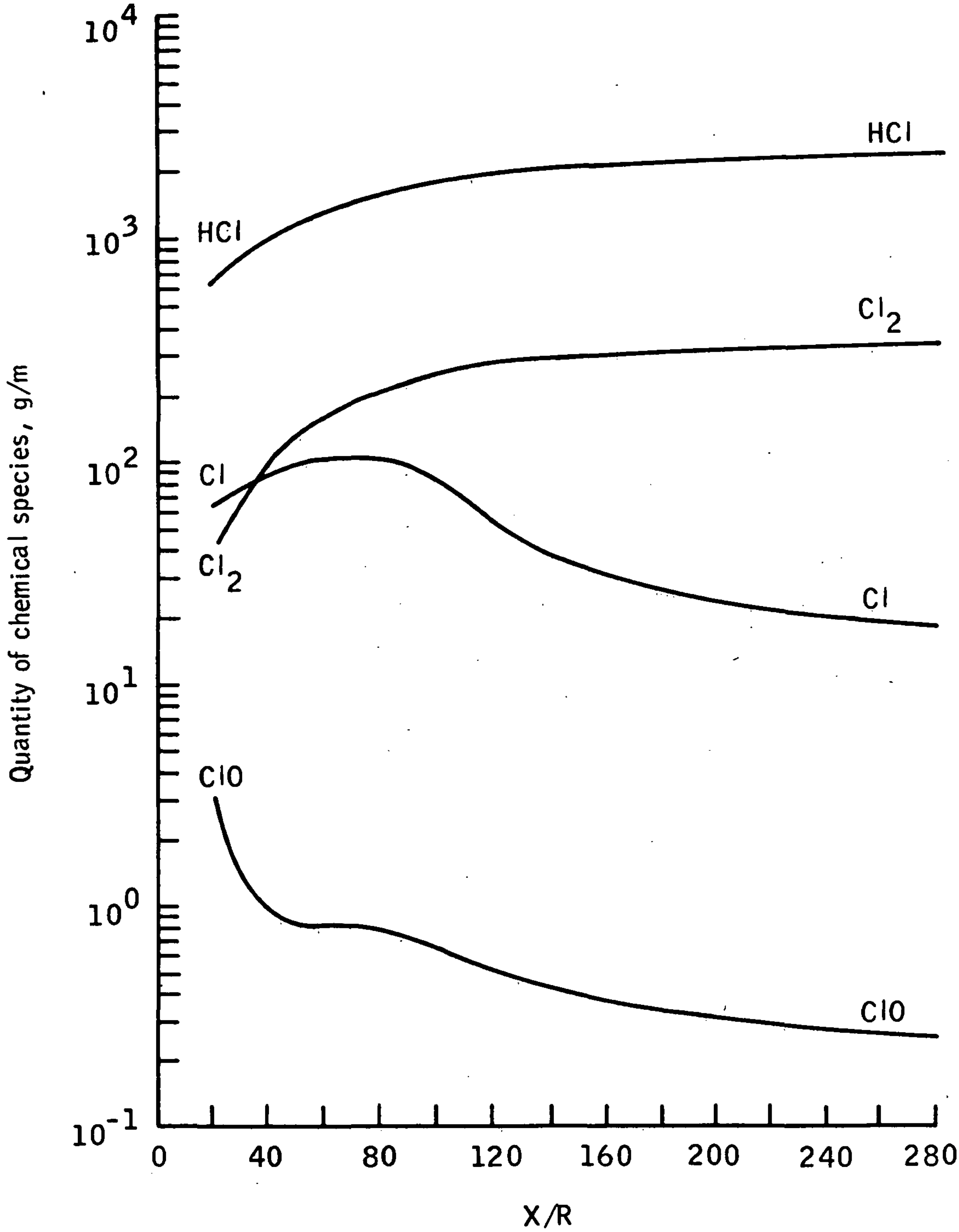


Figure A-4.- Approach to an asymptotic value of the quantity of chlorine species per meter downstream of a plume from a Shuttle motor at 5 kilometers altitude.

APPENDIX B - CLOUD-CENTERED DIFFUSION ESTIMATES

J. Briscoe Stephens of the NASA George C. Marshall Space Flight Center prepared the figures in this appendix as part of his troposphere workshop presentation. The data represent some potential "worst cases" for effluent production.

Figure B-1 is a graph showing the "worst-case" and "best-case" bounds of the predicted hydrogen chloride (HCl) and aluminum oxide (Al_2O_3) concentrations for 45 Shuttle launches using 1969 meteorological data. The average HCl concentration is 1.44 p/m ± 1.42 p/m with a 96-percent confidence. Figures B-2, B-3, and B-4 show predicted HCl concentration, predicted HCl dosage, and predicted HCl time-mean concentration for weather conditions on January 8, 1969. Figures B-5, B-6, and B-7 are graphs of these same factors for weather conditions on November 16, 1969.

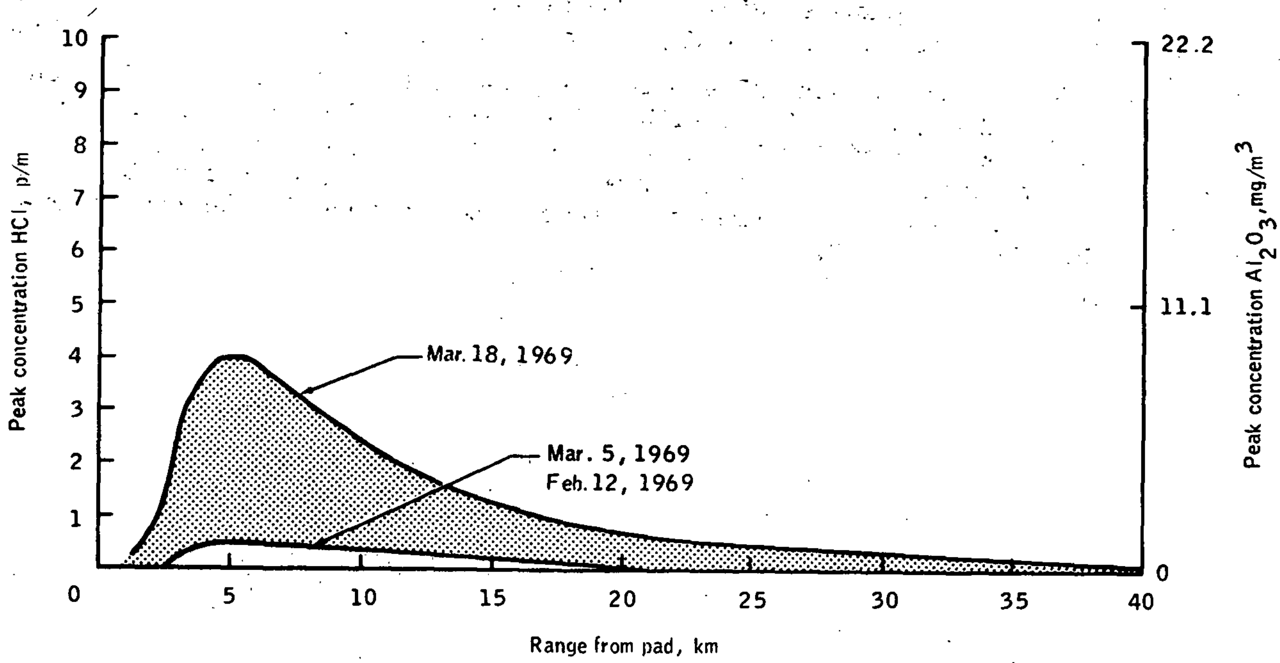


Figure B-1.- Preliminary Space Shuttle air quality predictions (45 launches, 96-percent confidence that HCl concentration from the launch is 1.44 ± 1.42 p/m).

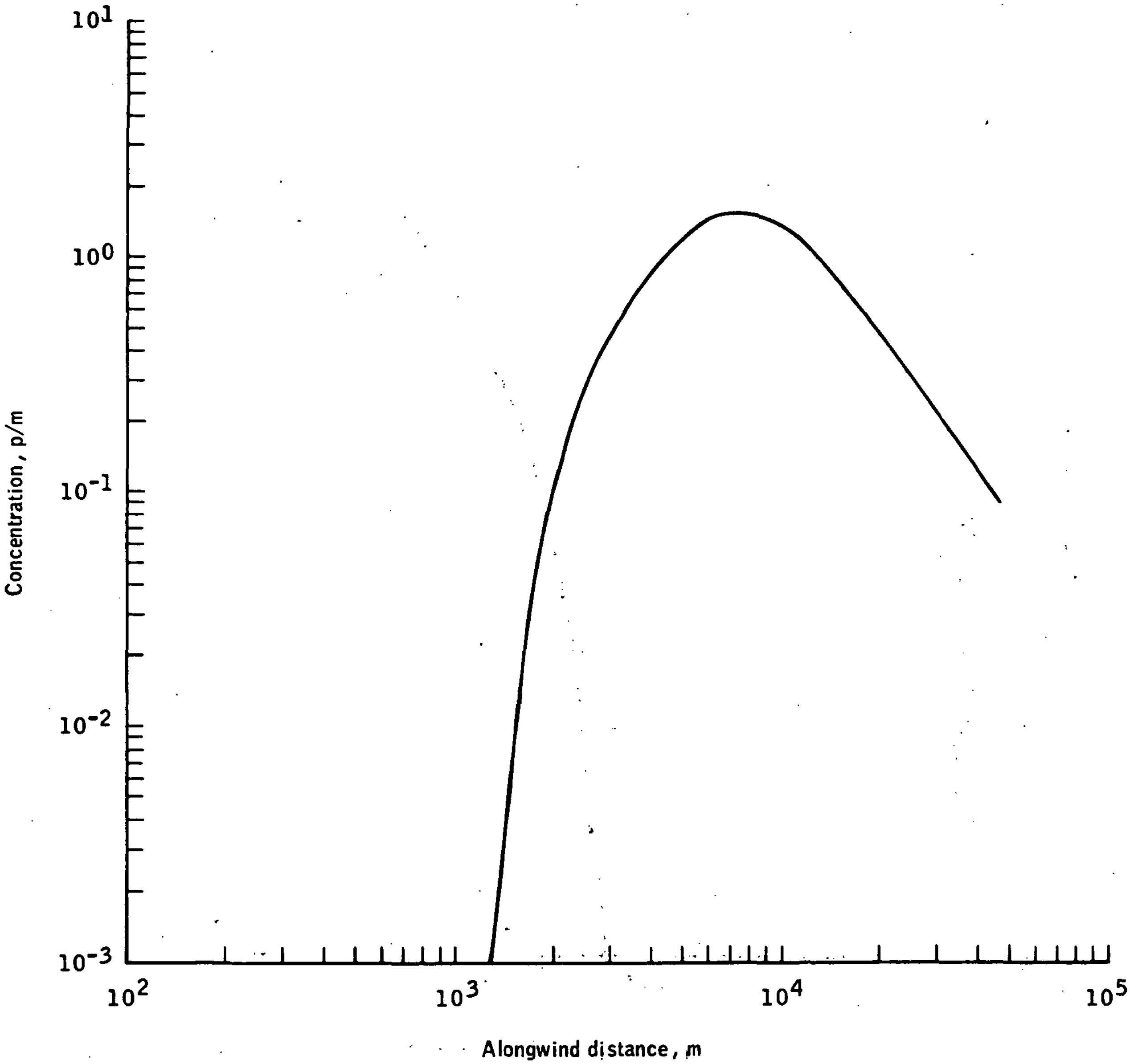


Figure B-2.- Maximum centerline HCl concentration at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 01/08/69, 1200 Greenwich mean time (GMT); adjusted cloud stabilization height 979.2 meters; range, 261.0 meters; azimuth bearing, 80.28°; maximum concentration, 1.52 p/m).

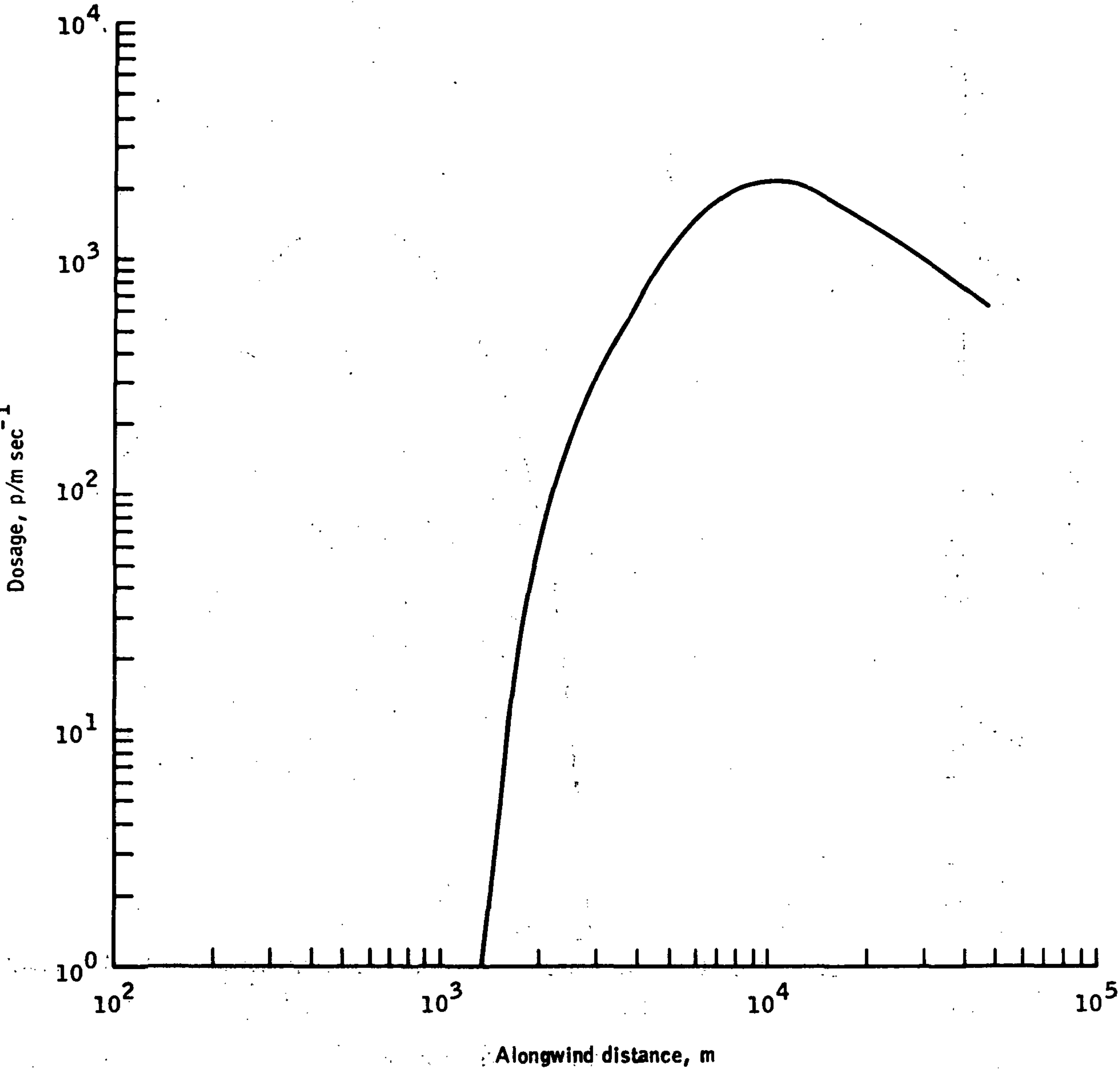


Figure B-3.- Maximum centerline HCl dosage at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 01/08/69, 1200 GMT; adjusted cloud stabilization height, 979.2 meters; range, 261.0 meters; azimuth bearing, 80.28°; maximum dosage, 2176 p/m sec^{-1}).

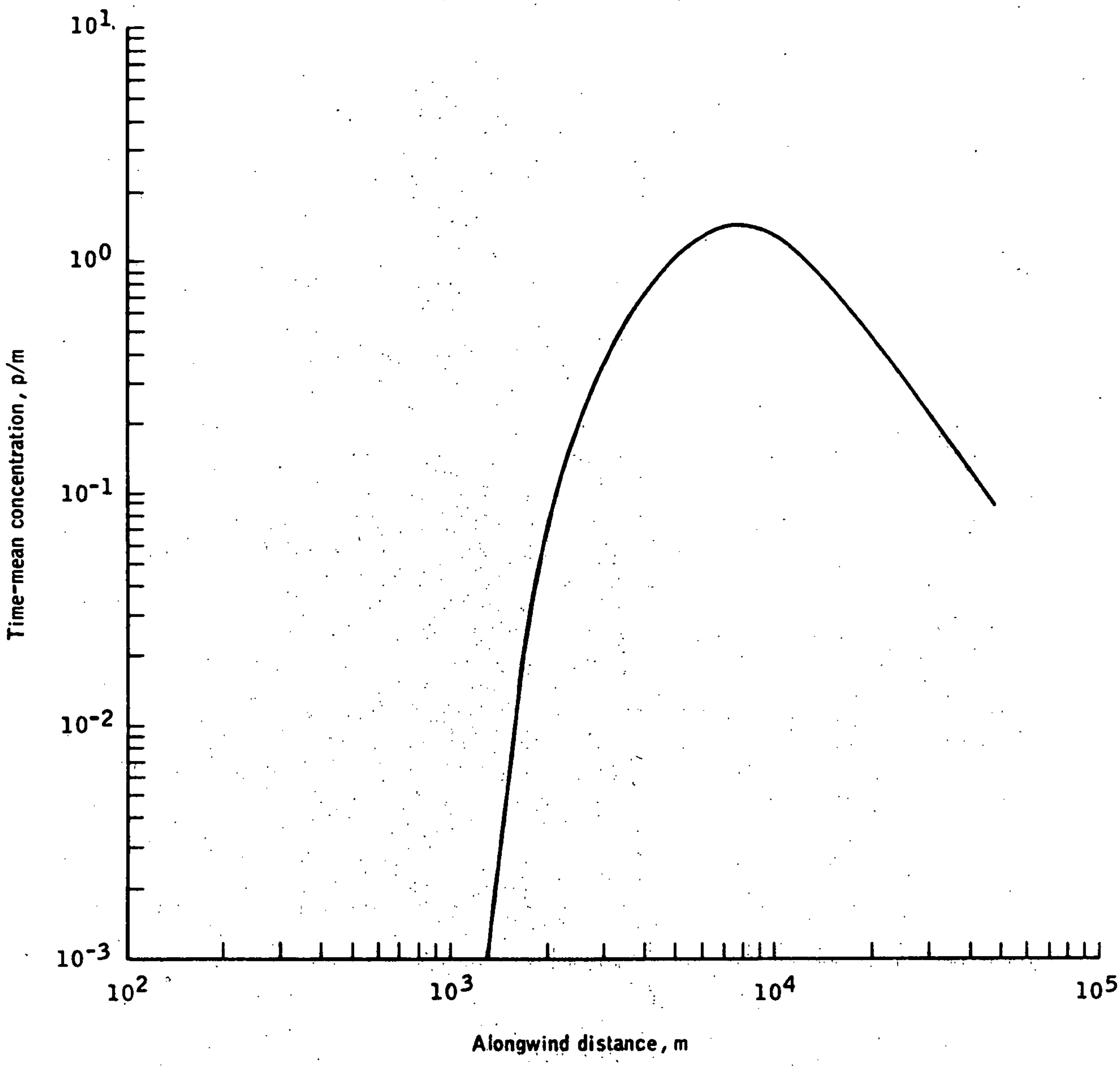


Figure B-4.- Maximum centerline HCl 10-minute time-mean concentration at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 01/08/69, 1200 GMT; adjusted cloud stabilization height, 979.2 meters; range, 261.0 meters; azimuth bearing, 80.28°; maximum 10-minute time-mean concentration, 1.45 p/m).

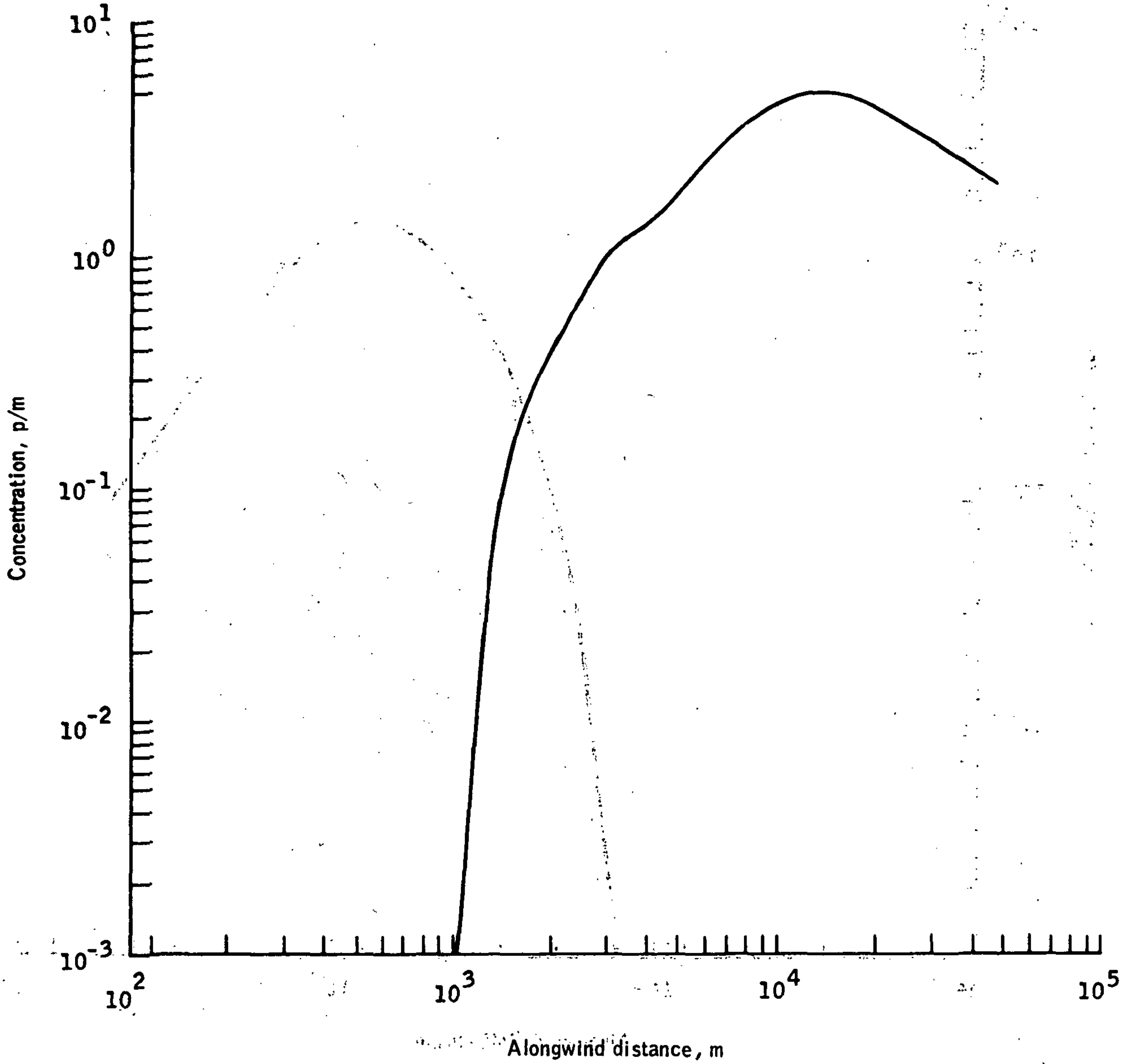


Figure B-5.- Maximum centerline HCl concentration at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 11/16/69, 1200 GMT; adjusted cloud stabilization height, 1135.6 meters; range, 1062.8 meters; azimuth bearing, 194.8°; maximum concentration, 5.03 p/m).

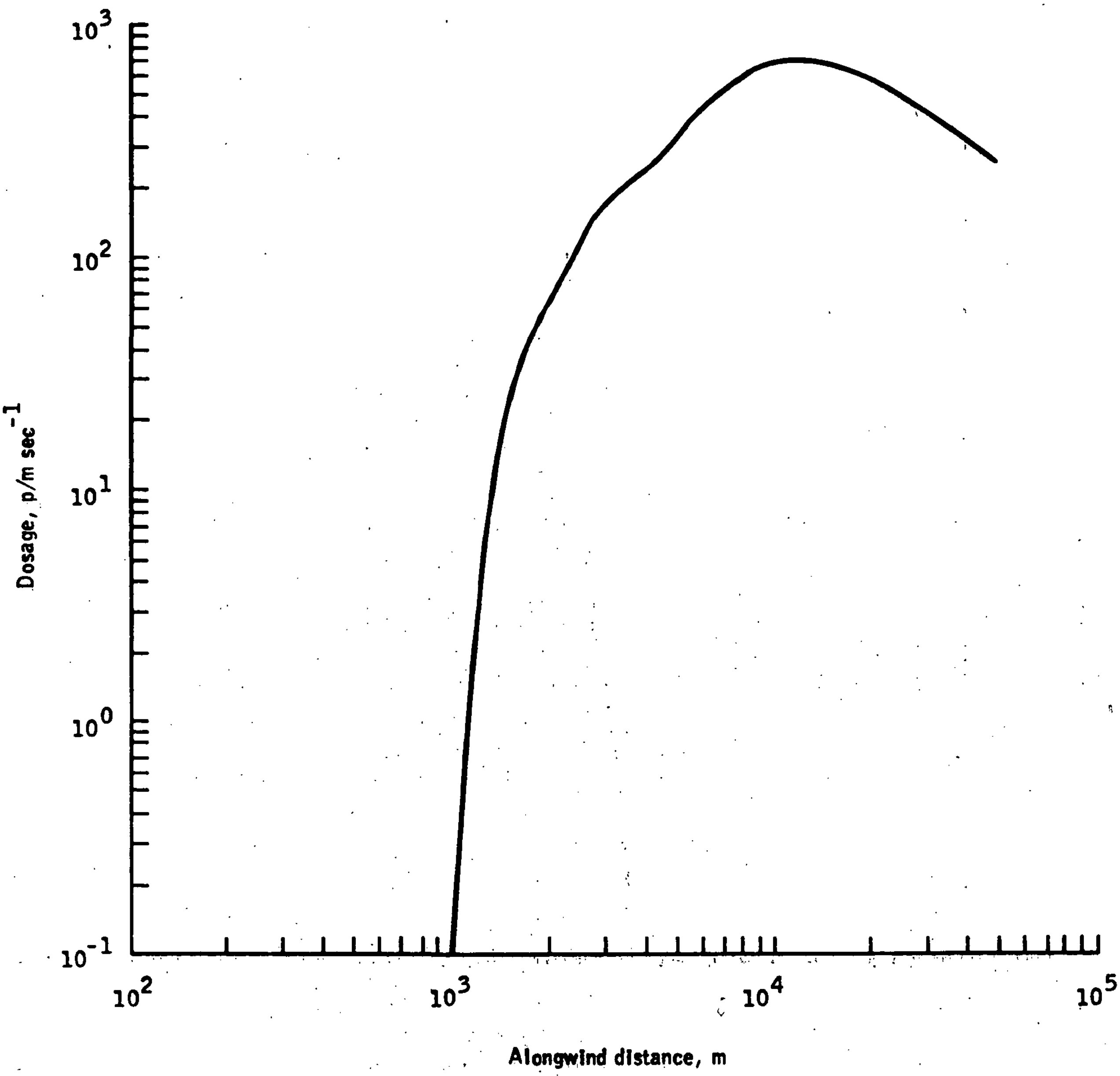


Figure B-6.- Maximum centerline HCl dosage in p/m sec^{-1} at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 11/16/69, 1200 GMT; adjusted cloud stabilization height, 1135.6 meters; range, 1062.8 meters; azimuth bearing, 194.8°; maximum dosage 719 p/m sec^{-1}).

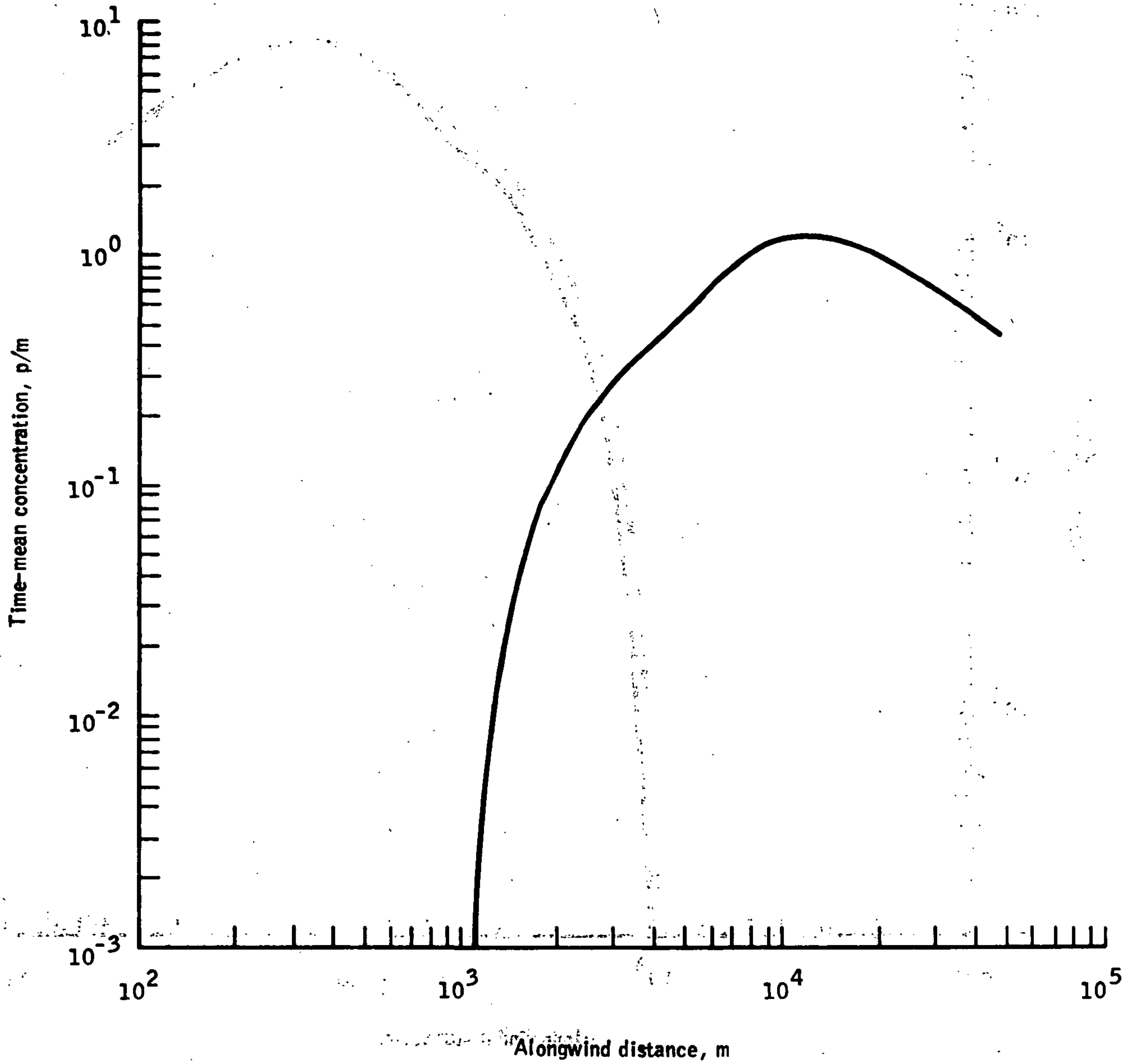


Figure B-7.- Maximum centerline HCl 10-minute time-mean concentration at a height of 0 meter downwind from a Space Shuttle normal launch (model 4; meteorological case 11/16/69, 1200 GMT; adjusted cloud stabilization height, 1135.6 meters; range, 1062.8 meters; azimuth bearing, 194.8°; maximum 10-minute time-mean concentration, 1.2 p/m).

APPENDIX C - GROUND CLOUD MEASUREMENTS

This appendix includes two work-in-progress reports. The reports are "Titan III Particulate Measurements" by H. S. Wagner, G. L. Gregory, and K. H. Crumbly, all at the NASA Langley Research Center (LaRC), and "Model-Measurement Comparison for Hydrogen Chloride" by G. L. Gregory of LaRC. Also included are excerpts from G. L. Gregory's workshop presentation that expands on the two previous reports. The references, tables, and figures for all the material are included at the end of this appendix; a single numbering system is used for all three reports.

TITAN III PARTICULATE MEASUREMENTS

The Environmental Impact Statement (EIS)[1] considers the fallout of the aluminum oxide (Al_2O_3) in the vicinity of the launch pads on page 40 and indicates that "...no significant fallout on land is envisioned...." The total Al_2O_3 burden deposited during the first 2 kilometers of flight will be approximately 69×10^6 grams. (See table 5A in the EIS). If it is assumed, as a worst case, that all the Al_2O_3 emitted in the troposhere (7×10^7 grams) is deposited in a corridor beneath the ground cloud track, and that corridor is 2 kilometers wide by 10 kilometers long; then the Al_2O_3 surface deposition would be approximately 3 g/m^2. However, the chemical analysis of the total suspended particulates collected during the Titan III measurement program indicates that the ratio of the total burden to the Al_2O_3 is somewhere in the range from 10 to 100. By using this factor as a multiplier for the calculated Al_2O_3 deposition, the total surface deposition including entrained debris could be anywhere from 30 to 300 g/m^2. This is much larger than the 5.8 g/m^2 shown on page 40 of the EIS.

Additional comparisons can be made with average dust fall rates for cities; these rates are given in textbooks such as reference C-1. They give monthly dust fall rates, which can be translated into daily rates that would range from 0.1 to 1.0 g/m^2/day. They also characterize "very dusty locations" by a dust fall rate of 20 g/m^2/day. From this simple analysis, each launch obviously represents a significant perturbation of the local particulate population. A

---

[1] 1972 Space Shuttle Environmental Impact Statement.

more detailed and rigorous analysis is underway to extend the current plume calculations to account for the settling of the "larger" particulate matter during the tropospheric ground cloud formation process so that investigators can make accurate predictions of the local particulate burdens.

As part of the launch vehicle effluent (LVE) program, particulate measurements have been made for seven Titan III launches at NASA John F. Kennedy Space Center (KSC). These measurements have been at ground level (0.1 to 15 kilometers from pad) and in the stabilized ground cloud (3 to 50 minutes after launch). In addition, the measurements have been made for a number of meteorological conditions, times of day, and seasons of the year (figs. C-1 to C-4 and table C-I). Based on this set of seven measurements (data analysis for two launches not yet complete), the following conclusions appear justified.

The particle loading as the result of a launch is not a major environmental problem. For most launches, particle loading at ground level is of the order of a few hundred micrograms per cubic meter (ref. C-2), relatively close (less than 2 or 3 kilometers) to the launch site, and exists for a few minutes at most. The Environmental Protection Agency (EPA) standards which must be addressed are based on 24-hour averages and annual averages:

Primary standard -

24-hour average: 260 $\mu g/m^3$ (not to be exceeded but once a year)

Yearly average: 75 $\mu g/m^3$

Secondary standard -

24-hour average: 150 $\mu g/m^3$ (not to be exceeded but once a year)

Yearly average: 60 $\mu g/m^3$

These standards, as well as the launch measurements, are for total suspended particles. At distances from the launch pad greater than 10 kilometers where uncontrolled population could be affected, the suspended particle measurements obtained during the launches are below 100 $\mu g/m^3$ (instantaneous value) and pose less of a problem.

For the in-cloud airborne measurements in the stabilized ground cloud, total suspended particle loadings are higher — ranging from 300 to 1200 $\mu g/m^3$ during the first 10 minutes or so after launch. While these loadings are quite high as compared to EPA standards, it must be remembered that these loadings exist for only a few minutes and, even if the stabilized ground cloud is allowed to intersect the ground, the EPA standards as they now exist would not be exceeded. Thus, a case can easily be built that the particles, in themselves, are not a major environmental impact as referenced to existing EPA standards. Furthermore, there are no indications that the EPA standards for total suspended particles will change.

Although the existing EPA particulate standards will not be violated, there are several additional aspects of the solid rocket motor (SRM) particle problem that might result in environmental problems. These are the annoyance factor and the potential for the particles to become acidic because of the presence of hydrogen chloride (HCl). The annoyance factor is based on observations from the LVE program. It has been the observation of the LVE team that a large percentage of the particle fallout experienced in the field has been large particles (not suspended). Although these particles do not present a health problem directly (too large for respiratory system), they do represent an annoyance because the larger particles can be detected both physically and in some cases visually by the public.

Two questions are evident: First, how far from the launch pad will this problem continue to occur: and second, what will the public response be? The data base to answer both of these question is limited. To date, the majority of particle measurements have been for suspended particles; thus, any existing data as to "how far" are based only on fieldteam observations. Based on these observations, the large particle fallout has been observed for distances of at least 5 kilometers and, potentially, may be experienced at distances where the uncontrolled public is residing. The answer as to "public response" is an open question. The second problem area is the acidity question. Laboratory work[2] has shown that the particles can act as nuclei for both the condensation of water (H_2O) and HCl. The result is, then, not an inert particle but an acid particle. In this case, the question of the particles being a health hazard (suspended) or an annoyance (large) is somewhat academic for the Shuttle's environmental impact, because both will result in public displeasure. Field measurements do show the existence of a highly acid aerosol 10 to 15 kilometers from the pad. These measurements are spotted pH paper (pH $\approx$ 1). In addition, preliminary analysis shows that these pH papers also show an abundance of aluminum (Al), suggesting the Al_2O_3 may be the carrier. In summary, these two particle problems cannot be dismissed at this point (particularly the acid particle problem). Additional field, laboratory, and analytical studies must be planned to answer these questions.

A third area of concern is the NASA George C. Marshall Space Flight Center (MSFC) model treatment of particulates. As shown in figures C-1 to C-4, the model consistently predicts higher (factor of 1000) ground level and in-cloud particle concentrations compared to what is measured. This is somewhat expected because the model used for these calculations (model 4) treats the particles as a gas, does not allow for particle sizing, and does not allow for large particle fallout. In addition, measurements are only for suspended particles. To add credibility to the NASA EIS, one must be able to do a mass balance for particles to show that all the particles are accounted for and that NASA understands the problem. A mass balance with the existing data (or theory) cannot be made because a large portion of the particles are unaccounted for. This

---

[2]Unpublished data prepared for the workshop by W. R. Cofer, III, and G. L. Pellet of LaRC.

problem is magnified when one considers that the particle loading, typically measured at launch (ref. C-2), shows a large amount of debris.

MODEL-MEASUREMENT COMPARISON FOR HYDROGEN CHLORIDE

The purpose of this report is to briefly compare model HCl predictions at the surface with launch-monitoring measurements obtained from December 1974 through September 1975 (four Titan launches) at KSC. Because this report is a preliminary analysis considering only approximately 10 percent of the data, it is subject to revision as the complete (cloud track, airborne results, particle results) data sets and postlaunch predictions are compared. Predictions are postlaunch calculations made by MSFC several months after launch. This preliminary comparison is useful because it may reflect the position of NASA if the existing models, techniques, and committed resources were used at this time to assess, postlaunch, the environmental impact for a given launch.

Before discussing a model-measurement comparison, it is important to briefly discuss model-measurement comparison theory. Because the MSFC model is basically a statistical one, it can predict what will happen on the average if given, say, 100 chances to study the event; one must question the validity of comparing measurements from only one event with the model output. Comparisons for different launches do not satisfy the basic argument because a different launch is, for all practical purposes, a new event which, theory-wise, should be measured many times. Typically, the comment has been made that comparison of a single set of measurements with the MSFC model (statistical) predictions as what will happen on the average is an invalid approach. While this statement is theoretically correct, there appears to be merit and correctness in making model-measurement comparisons on a one-to-one basis for several launches. The merit is that this is the way in which NASA is planning to use the MSFC model. As it currently stands, the model will be used to predict the environmental impact for a given launch. Regardless of the type of model, it must be verified in the mode in which it is to be used. If measurements and model predictions agree reasonably well, then the model will be shown to be a good estimator of what happens for a single event. If comparisons are unfavorable, it is not the result of an "invalid comparison" but more likely a poor choice of the type of model required. An analogous problem is the attempt to estimate the true variance of a random statistical process from a study of only three events of that process. It should be noted that there are theoretical approaches for relating single event to general statistical concepts, and these approaches are being considered in the LVE problem area. With these comments in mind, comparisons can be considered.

During four Titan launches, 35 sites were instrumented to monitor HCl concentration: 7 sites, December 1974; 9 sites, May 1975; 10 sites, August 1975; and 9 sites, September 1975. The comparisons only apply to the measured or predicted maximum HCl concentration at these locations. No consideration is given to the fact that the predicted cloud path may have been different from the actual (observed) path (that is, possible meteorological errors). In some cases it can be speculated, and rightly so, that the discrepancies between model and measurements are largely due to meteorological considerations. The HCl comparisons are in three areas.

1. Comparison at sites where positive HCl measurements were recorded

2. Comparison at all 35 instrumented sites

3. Comparison at those instrumented sites where the model predicted HCl concentrations were 0.1 p/m or greater

Comparison at Positive Data Sites

Of the 35 sites, 10 sites obtained positive HCl data; these data are shown in table C-II. Based on these 10 comparisons, the model predictions were high 5 times and low 5 times. With the exception of two sites, the model was within a factor of 10 (10 to 0.1) of the measured maximum HCl concentrations. If one allows a $\pm 10^\circ$ error in the specification of the site location (approximately the same as assuming a $\pm 10^\circ$ error in cloud path) and allows this $\pm 10^\circ$ to represent an error band for the prediction, then for the 10 comparisons, the model was low twice, high four times, and within the error band four times. (This is probably a reasonable assumption for an error band because typically, a prediction of 0.2 p/m will transpose into 0.2 ± 0.1 p/m.) A similar comparison as a function of site distance from the pad is shown in table C-III. As indicated here, no strong trends exist with respect to distance from the pad.

Comparison at All Sites

A comparison at all of the 35 sites using the $\pm 10^\circ$ error assumption resulted in the model being high 21 times, low 3 times, and within the error band 11 times.

Comparison at Sites Where Predictions Were ≥ 0.1 p/m

A comparison was made at sites where HCl predictions were ≥ 0.1 p/m. The importance of this particular comparison is that it includes those sites where a concentration was predicted at a level where HCl starts to be offensive (odor, etc.) and, thus, of concern to the public and environmental regulatory authorities. Of the 35 instrumented sites, 18 had predictions of 0.1 p/m or higher (table C-IV).

Based on this type of comparison, the model routinely predicts high by as much as a factor of 50 or 100. However, note that 15 of these 18 comparison sites showed no HCl measurements, thus indicating that this particular comparison may be biased by errors in predicting the cloud path.

At this particular time, the model can best be summarized as generally predicting high; and, when cloud trajectory is adequately predicted, model predictions appear to be adequate to a factor of 10. A word of caution must be stated at this point. These comparisons are preliminary results on postlaunch model predictions. These comparisons add little confidence to the accuracy of a prelaunch effluent forecast. For the reasons stated below, prelaunch forecasting is believed to be much less accurate.

1. Forecast must be based on minus-time meteorology rather than actual-launch meteorology.

2. Forecasts must be completed in real time not allowing trial-and-error or parametric evaluations of such key model inputs as layering of atmosphere, cloud stabilization height, and cloud geometry.

3. Forecasts must be made without knowledge of experimental measurement data.

MEASUREMENTS OF PHYSICAL EFFECTS (PRESENTATION EXCERPTS)

Two Space Shuttle effluents of most concern in the atmosphere are HCl and particulates. Figure C-5 consists of graphs showing measurements of these two effluents attained during several airborne passes through an exhaust cloud produced by a Titan III launch. Plots of effluent in-cloud concentration as a function of time are shown for HCl and Al_2O_3 in figure C-6 for several Titan III launches. Similar data for oxides of nitrogen (NO_x) are in figure C-7. The maximum readings of in-cloud readings for several effluents during six different launches are shown in table C-I. The effluent ratios of Al_2O_3 to NO_x and HCl to NO_x are shown in figure C-8.

Summary of Airborne Measurements

Future studies must note that measured Titan III peak concentrations are lower than anticipated at initiation of the measurement program. If dilution ratios and air entrainment coefficients for the Shuttle cloud are similar to the Titan III, then the same low concentrations would be expected.

While the airborne data do not have a direct impact on the EIS, it does affect the EIS areas of precipitation scavenging (that is, acid rains and acid particles), weather modification, model confidence, and particulate mass balance. In particular, it decreases the threat of precipitation scavenging.

Ground Level Measurement Summary

During seven Titan launches, 43 sites (1 to 20 kilometers from the launch site) were instrumented to measure HCl. Of these sites, 32 recorded no observable readings (instrument detection limit, 0.005 p/m), 8 measured below 0.05 p/m, 2 measured from 0.1 to 1 p/m, and 1 (the maximum reading) measured 1.3 p/m.

This last maximum reading plus several others of interest are shown in table C-V. Notice that the highest observed dosage at a downwind site was approximately 200 p/m sec^{-1} (1.3 p/m) at 5 kilometers. The HCl readings at this site several minutes before, during, and after the peak reading are graphed in figure C-9. A similar graph of dosage compared to time (fig. C-10) shows the second highest observed concentration. Figure C-11 illustrates the rise and stabilization heights of exhaust clouds from the seven launches.

Field observations indicate that the odor threshold for HCl appears to be approximately 0.05 p/m. Odor was detected at all sites where concentration was 0.1 p/m or higher. The threshold for irritation of eyes and skin appears to be below 1 p/m.

Field measurements suggest that most HCl is in a gaseous phase rather than a liquid (hydrochloric acid) phase. Field measurements also indicate the presence of acidic particles or aerosol as far as 10 or 15 kilometers from the launching pad.

An acid rain did occur after the September 1975 Titan III launch.

Hydrogen Chloride Model (Measurement Comparisons)

Data from four Titan III launches provide a basis for model testing. The limitations of this testing were that maximum HCl concentrations at each site were used, no corrections were made for meteorological errors, the model was only used for postlaunch prediction, and as much as 10° error was allowed in figuring site location as related to the cloud path. With these limitations in mind, the following types of comparisons were made: all instrumented sites where positive HCl measurements were recorded, all instrumented sites, and all instrumented sites where the model predicted 0.1 p/m or higher.

Of 35 sites, 10 had recorded positive HCl measurements. In comparisons of these 10 sites, the following observations have been made.

1. The ratio of predicted maximum concentration to measured maximum concentration ranges from 0.03 to 27.

2. Generally (8 sites out of 10), the model predicted within a factor of 10 (ratio = 0.1 to 10).

3. The model predictions were too low twice, were within a 10° error band 2 times, and were high 4 times.

4. There was no obvious trend in model accuracy with distance from the pad.

There were 18 sites where the model predicted HCl concentrations of 0.1 p/m or higher. Of these 18 sites, 15 showed no measurable amounts of HCl (concentration greater than 0.005 p/m). At the 3 sites where the instruments did get readings, the model was high by a factor of 50.

In comparison of all 35 sites, the model predictions were low 3 times, within the 10^{o} error band 11 times, and high 21 times.

Particulate Measurements

Particulate measurements were made from 0.1 kilometer to 20 kilometers from the launching pad. At distances of 10 kilometers or more (which would affect the public), total suspended particulates measured were well below 100 $\mu g/m^3$ (instantaneous value), which is well below existing Environmental Protection Agency standards. However, a large percentage of particulate loading due to the launch is debris. Observations indicate that such heavy particles (not suspended) fall out at distances as far as 5 kilometers from the launch pad and, possibly, farther.

More exact data are needed, particularly in relation to two questions. Data are insufficient to make a particulate mass balance and to fully investigate the possibility suggested by measurements that particulates are an active site for both water and HCl. Figures C-1 to C-4 illustrate the disparity between modeled and measured concentrations of Al_2O_3 particulate.

Predictive Capability

Present modeling appears capable of providing reasonable assessment of effluent impact with a limited measurement program. The model is generally within a factor of 10 for maximum HCl concentration. For particulates, the model is consistently high; but — by using limited field data, past history, laboratory results, and model predictions — reasonable assessment is available.

Prelaunch capability for the model is not sufficient to stop a launch. The limits seem to be largely meteorological. During stable weather conditions, there is a reasonable chance to predict cloud path 1 to 2 hours before launch. Prior to 6 hours before launch, weather forecasting with accuracy enough to predict cloud path is very difficult.

In conclusion, if data are required only to corroborate the EIS and to validate any damage claims resulting from the launch, that capability will be available in the near future (present capabilities may even be sufficient). If data are required to make go/no go decisions for Space Shuttle launches and to establish routine launch constraints, that capability is not available at present.

SUMMARY AND PLANNING CONSIDERATIONS

The end goal of this research has been to assess any potential environmental effects of the Space Shuttle that might endanger lives or property, violate environmental regulations, or create a public nuisance. Any of these effects could necessitate costly changes in the program. With these thoughts in mind, the possible effects will be reviewed.

Aluminum oxide deposition rates will not violate EPA total suspended particulate standards. Similarly, total particulate deposition rates (Al_2O_3 plus debris) will not violate EPA total suspended particulate standards.

However, there are still some open questions. The total particulate deposition rate may be a public annoyance. The allowable limits for acid-coated Al_2O_3 particles have not been established. Acidic particulates might cause damage to plants and property. Finally, the particulate mass balance is inadequate; and, while this probably represents smaller effluent levels than previous estimates, the mass balance is a question that should be resolved.

Regarding HCl, effluent levels are within the National Research Council-National Academy of Sciences Committee on Toxicology's suggested guidelines; i.e.,

Occupational emergency exposure limit (EEL) . . .	30 p/m for 10 minutes
Short-term public limits (STPL)	4 p/m for 10 minutes (8 p/m peak)
	2 p/m for 30 or 60 minutes
Public emergency limits (PEL)	7 p/m for 10 minutes (14 p/m peak)
	3 p/m for 30 or 60 minutes

If these criteria are accepted by the public, there will be only minimal additional work to be done in the Shuttle environmental area. All pertinent research could be closed out in 1 to 2 years. At the launch site, only a minimal operational program would be required. Acid rain would be the main problem.

If for some reason these criteria are changed, further understanding of the problem becomes important. It would no longer be possible to argue that predictions or measurements are below the "acceptable" limits by an order of magnitude.

REFERENCES

C-1. Butcher, Samuel S.; and Charlson, Robert J.: Introduction to Air Chemistry. Academic Press, Inc. (New York), 1972

C-2. Gregory, G. L.; and Storey, R. W., Jr.: Effluent Sampling of Titan III-C Vehicle Exhaust. NASA TM X-3228, 1975

TABLE C-I.- MAXIMUM TITAN III IN-CLOUD EFFLUENTS[a]

Species	Maximum in-cloud effluents, for launch on -					
	May 30, 1974, 8:00 a.m., EST	Dec. 10, 1974, 2:11 a.m., EST	May 20, 1975, 9:04 a.m., EST	Aug. 20, 1975 4:22 p.m., EST	Sept. 9, 1975, 1:39 p.m., EST	Mar. 14, 1976, 8:25 p.m., EST
HCl, p/m	--	40	6	6	2	<1
Al_2O_3, $\mu g/m^3$	--	2600	1500	1400	120	(b)
CO, p/m	--	≈3	--	--	--	≈1
NO_x, p/b	800	--	435	1400	290	1100

[a]Maximum concentration observed; peaks for each species may not be for the same pass through the ground cloud.

[b]To be determined.

TABLE C-II.- DATA SUMMARY FOR 10 SITES OBTAINING POSITIVE HCl DATA

Launch	Azimuth from pad, deg	Distance from pad, km	Predicted HCl, p/m	Measured HCl, p/m	Ratio of measured to predicted
Dec. 1974	130	7	0.01	0.35	0.029
Dec. 1974	147	11.5	.15	.022	6.8
Dec. 1974	147	4	.22	.5	.44
May 1975	145	8	.03	.05	.6
May 1975	164	16	.21	.02	10.5
May 1975	176	13.9	.05	.025	2
Aug. 1975	329	7.2	<.01	.014	<.7
Sept. 1975	257	2.6	.16	.006	26.7
Sept. 1975	230	3.6	.01	.023	.44
Sept. 1975	241	5	.12	.04	3

TABLE C-III.- DATA COMPARISON AS A FUNCTION OF SITE DISTANCE FROM PAD

Distance from launch pad, km	Number of sites	Model high	Model low	Model within error band
≤5	4	2	1	1
>5 and ≤10	3	0	1	2
>10	3	2	0	1

TABLE C-IV.- COMPARISON AT SITES WITH HCl PREDICTIONS $\geq$0.1 p/m

Launch	Predicted HCl, p/m	Measured HCl, p/m	Ratio of measured to predicted
Dec. 1974	0.27	<0.005	>54
Dec. 1974	.15	.022	6.8
Dec. 1974	.22	.5	0.44
Dec. 1974	.24	<.005	>48
Dec. 1974	.19	<.005	>38
May 1975	.21	.02	10.5
May 1975	.21	<.04	>5.3
May 1975	.1	<.01	>10
Aug. 1975	.23	<.005	>46
Aug. 1975	.23	<.005	>46
Aug. 1975	.5	<.005	>100
Aug. 1975	.43	<.005	>85
Aug. 1975	.18	<.005	>36
Sept. 1975	.16	.006	26.7
Sept. 1975	.56	<.005	>112
Sept. 1975	.62	<.04	>15.5
Sept. 1975	.12	.040	3
Sept. 1975	.47	<.005	>94

TABLE C-V.- SELECTED HCl DOSAGE MEASUREMENTS

Launch	Site distance, km	Maximum concentration, p/m	Dosage, p/m sec^{-1}
May 1974	5.2	1.3	205
Dec. 1974	4.0	.5	15.2
Dec. 1974	7.0	.35	19.5
Dec. 1974	11.5	.022	6.2
Aug. 1975	7.2	.014	7.0

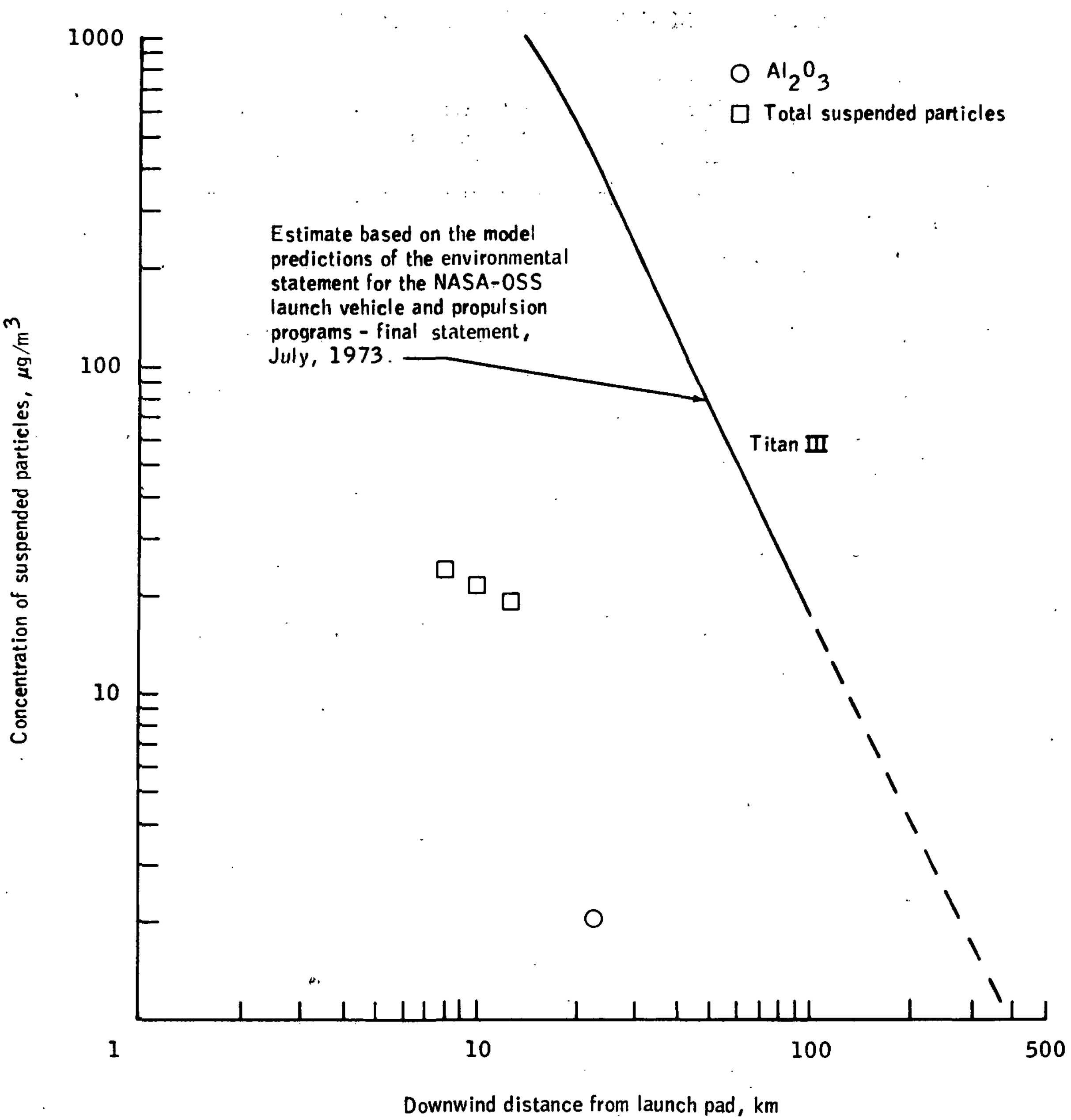


Figure C-1.- Measured (May 20, 1975) compared to estimated (spring) instantaneous peak aluminum oxide (Al_2O_3) concentration downwind of Titan III launch. Extrapolation shown by dotted line.

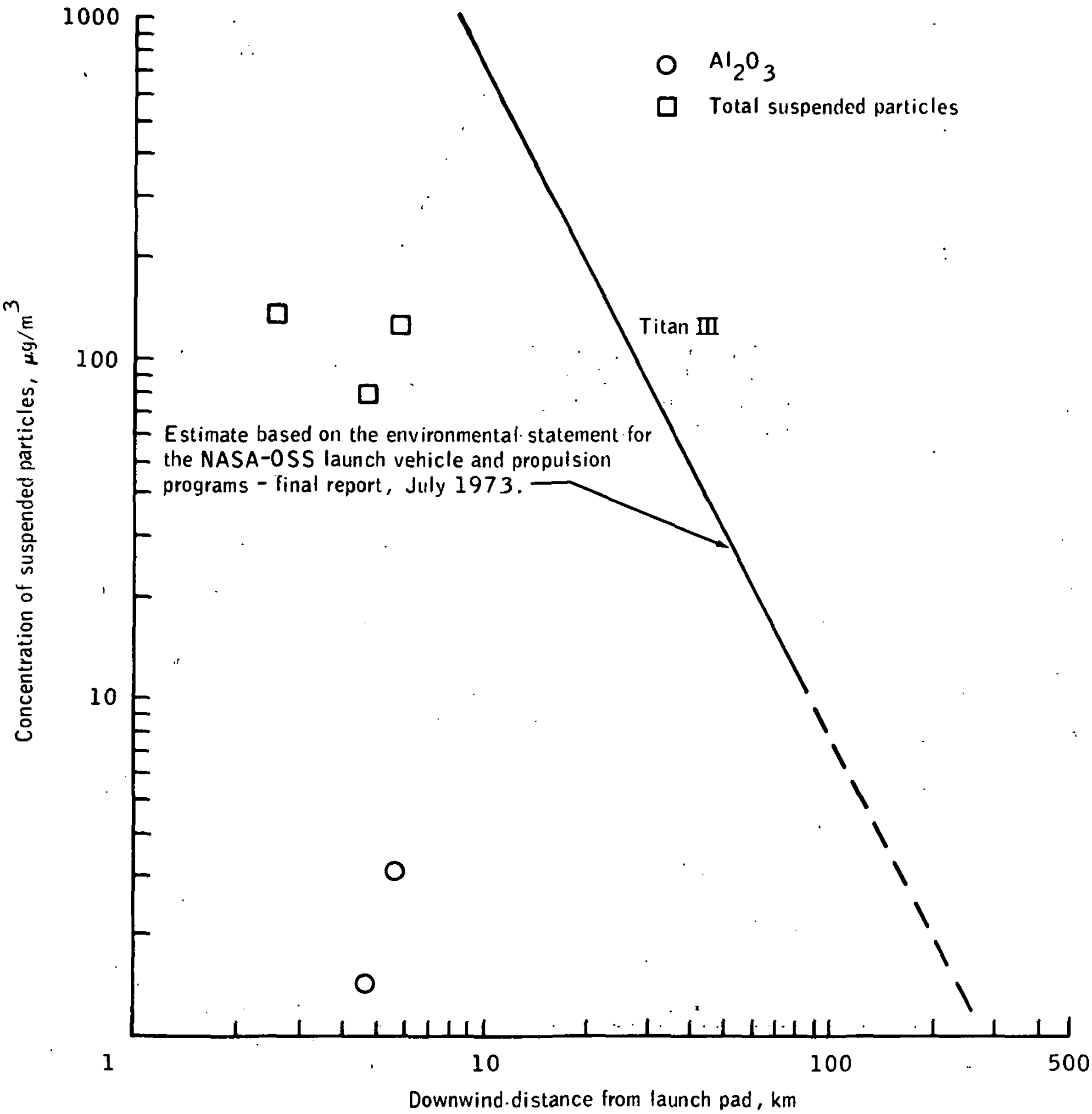


Figure C-2.- Measured (August 1975) compared to estimated (seabreeze conditions) instantaneous peak aluminum oxide (Al_2O_3) concentration downwind of Titan III launch. Extrapolation shown by dotted line.

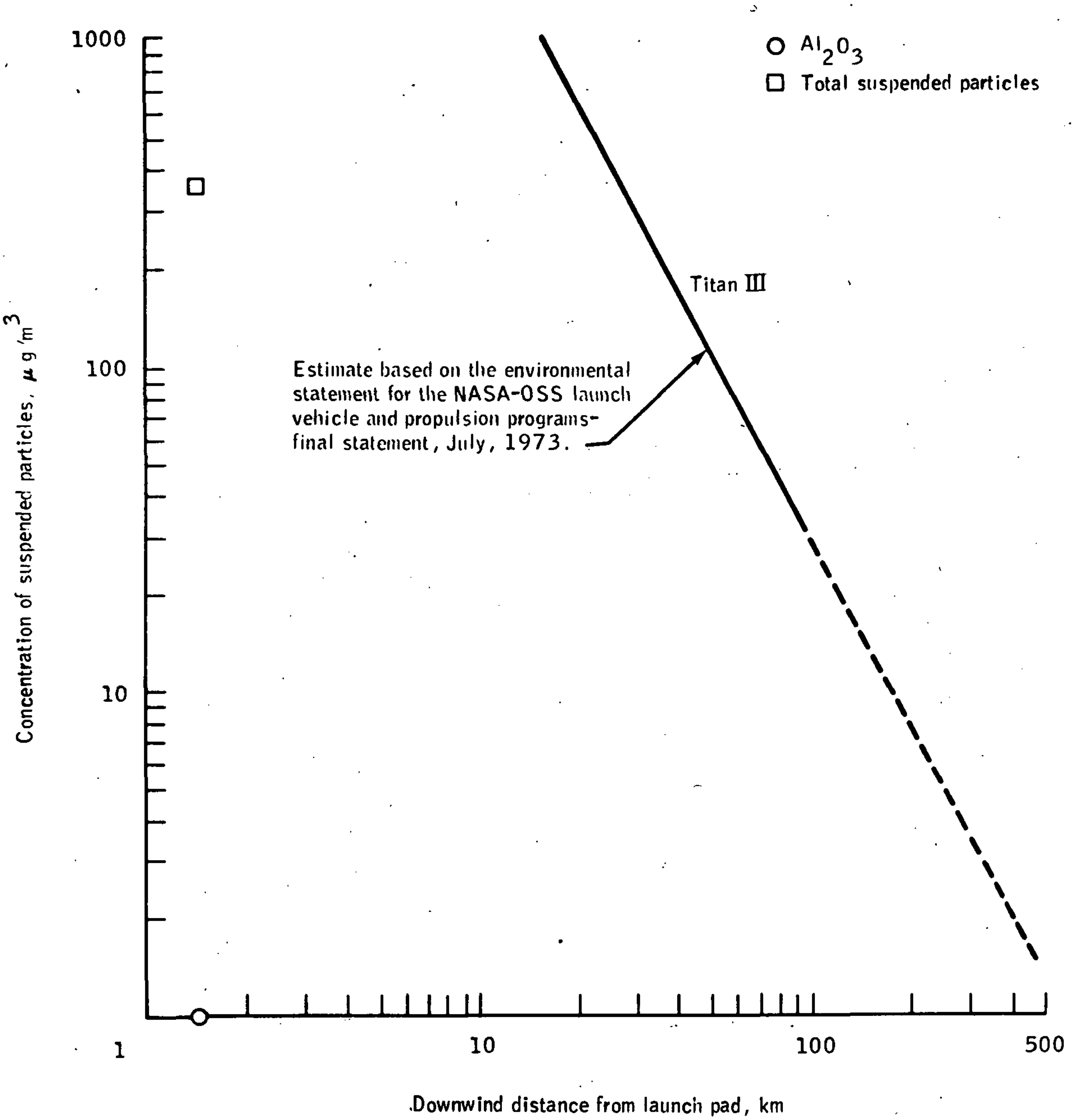


Figure C-3.- Measured (Feb. 11, 1974) compared to estimated (spring) instantaneous peak aluminum oxide (Al_2O_3) concentration downwind of Titan III launch. Extrapolation shown by dotted line.

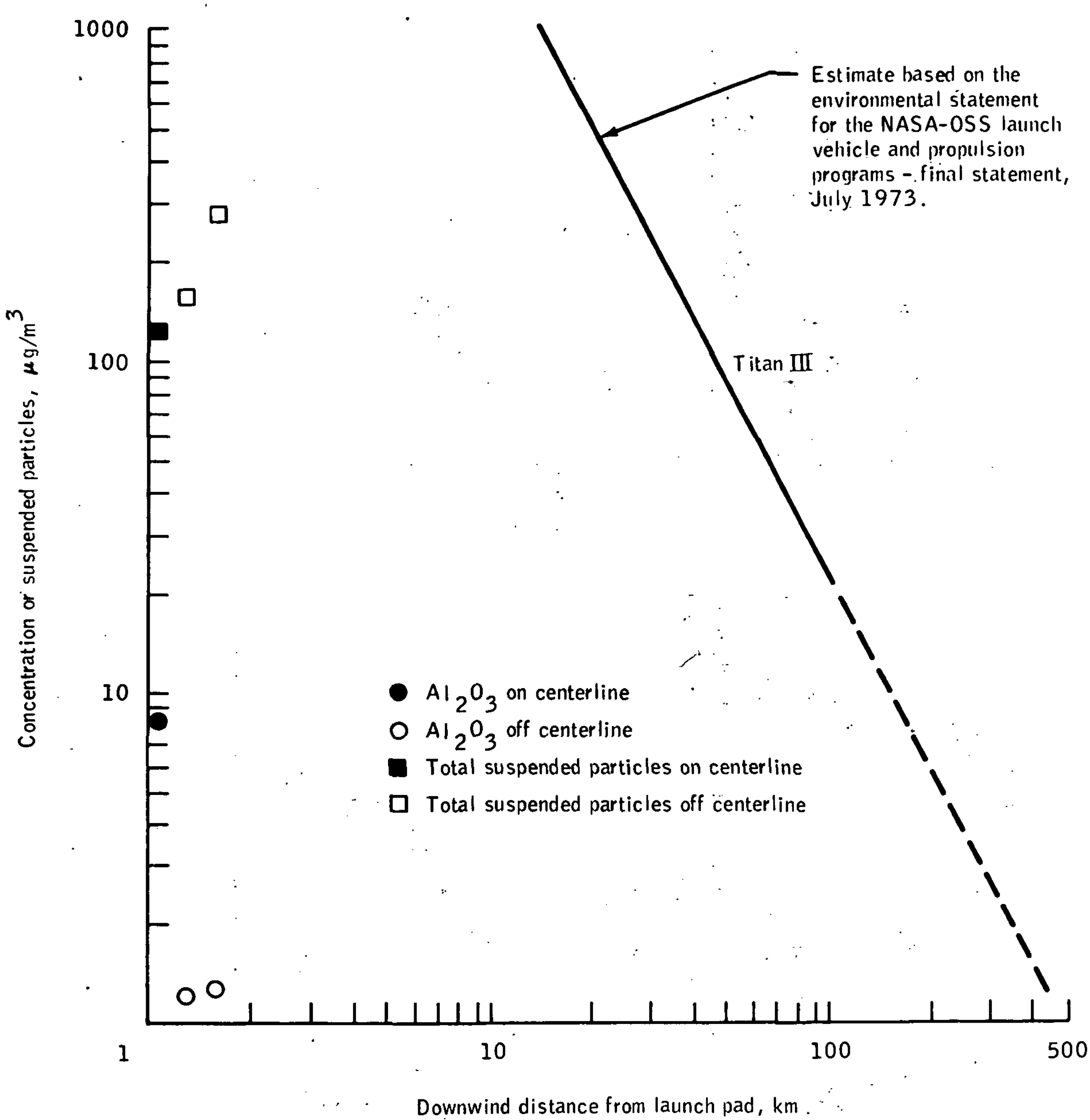


Figure C-4.- Measured (Dec. 13, 1973) compared to estimated (fall) instantaneous peak aluminum oxide (Al_2O_3) concentration downwind of Titan III launch. Extrapolation shown by dotted line.

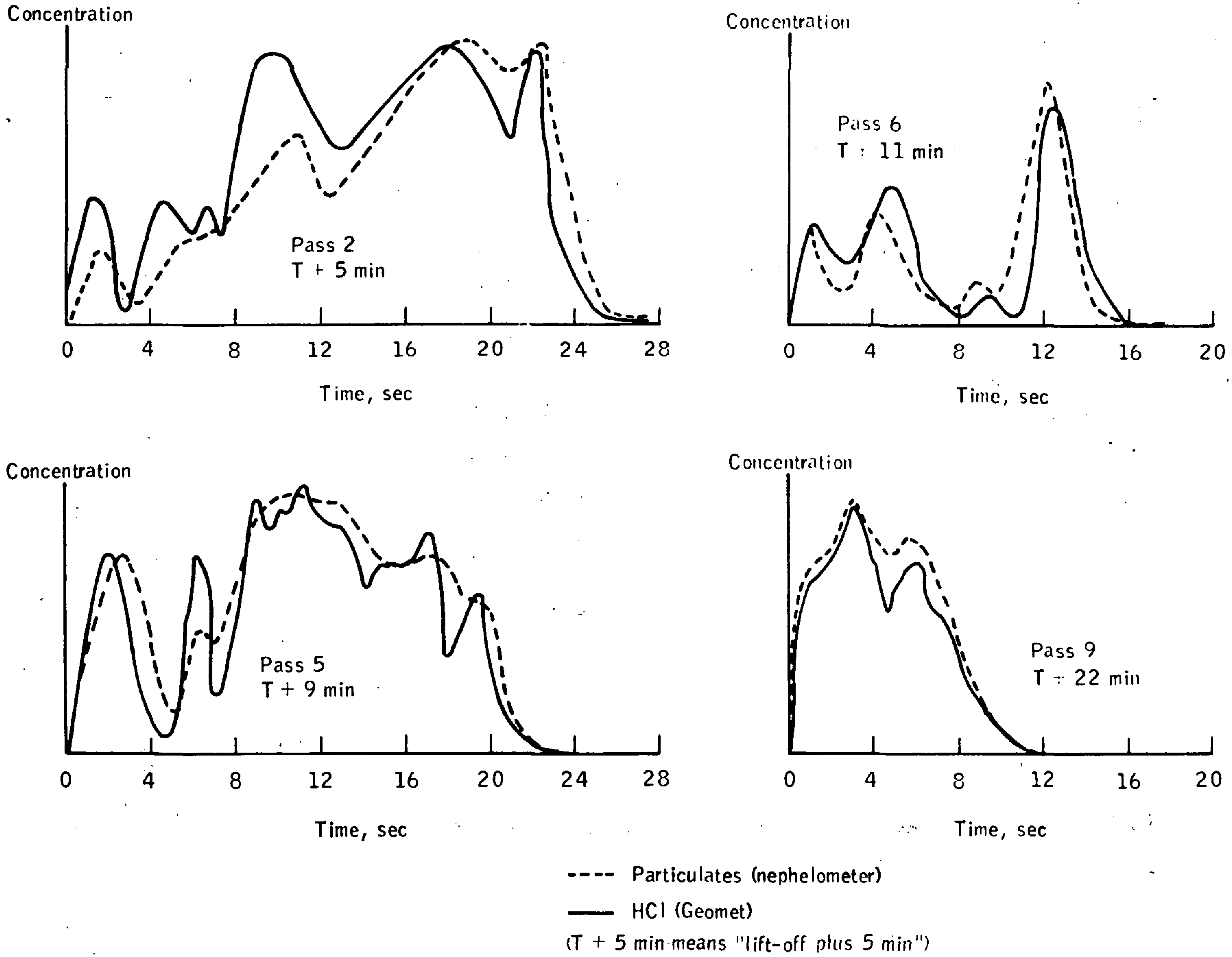


Figure C-5.- Airborne measurements of hydrogen chloride (HCl) and particulates after Titan III launch (Dec. 10, 1974).

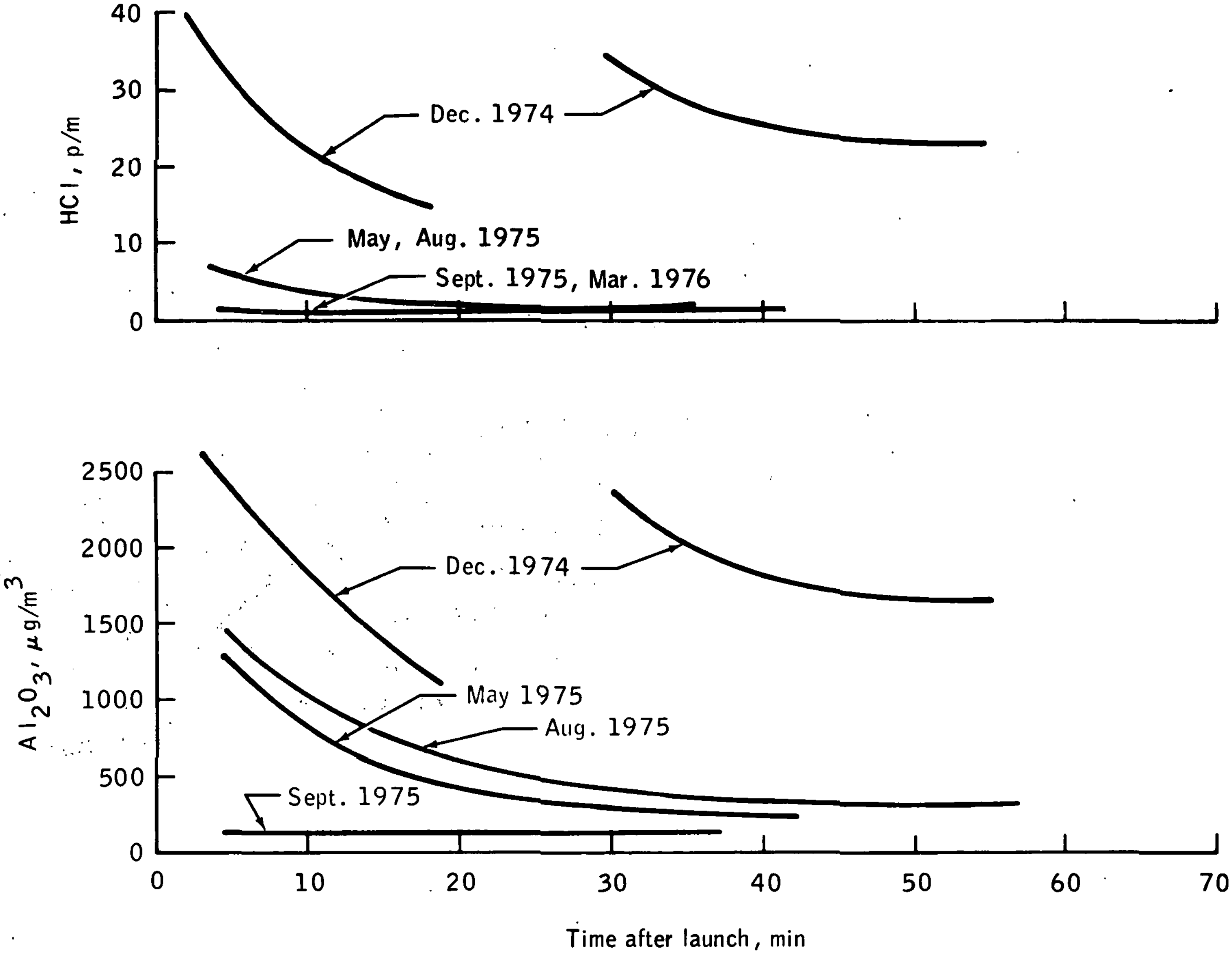


Figure C-6.- In-cloud launch vehicle effluent measurement (1974 to 1976) for hydrogen chloride (HCl) and aluminum oxide (Al_2O_3).

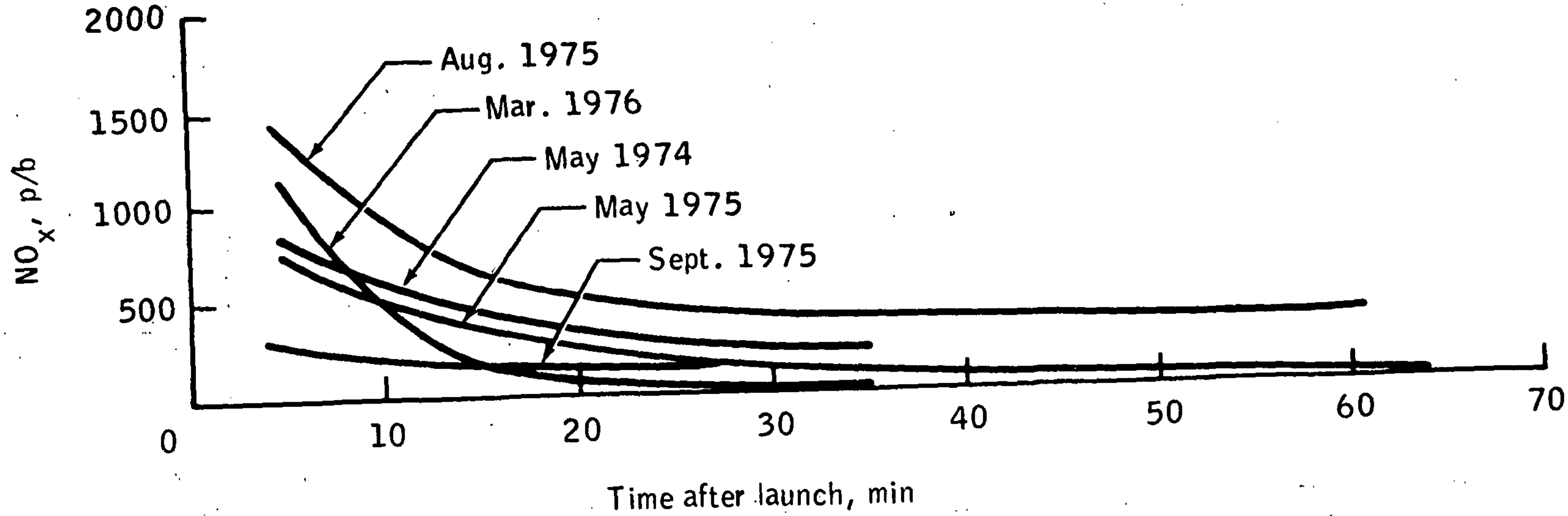


Figure C-7.- In-cloud launch vehicle effluent measurement (1974 to 1976) for oxides of nitrogen (NO_x).

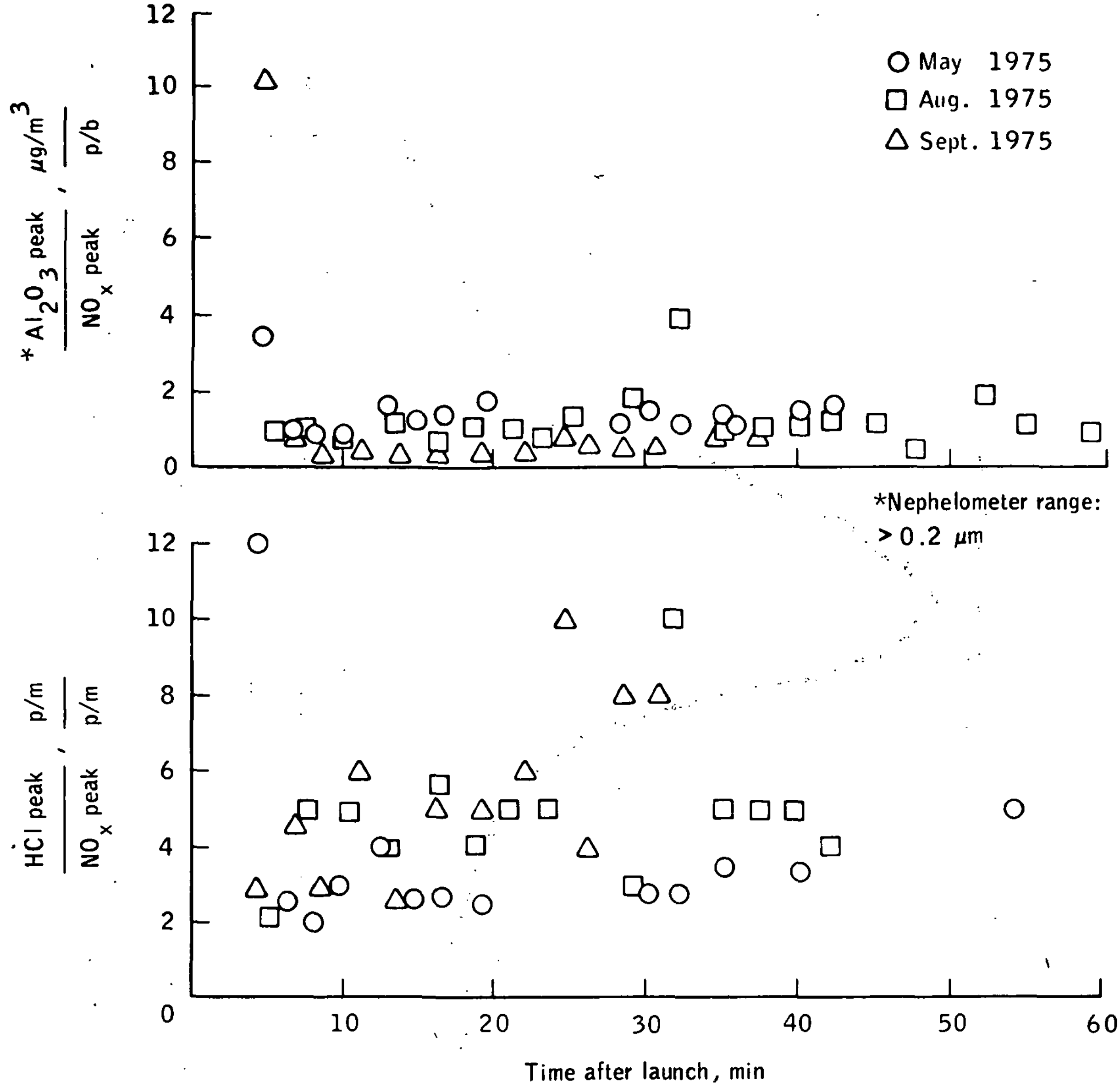


Figure C-8.- Effluent ratios for several compounds during three launches.

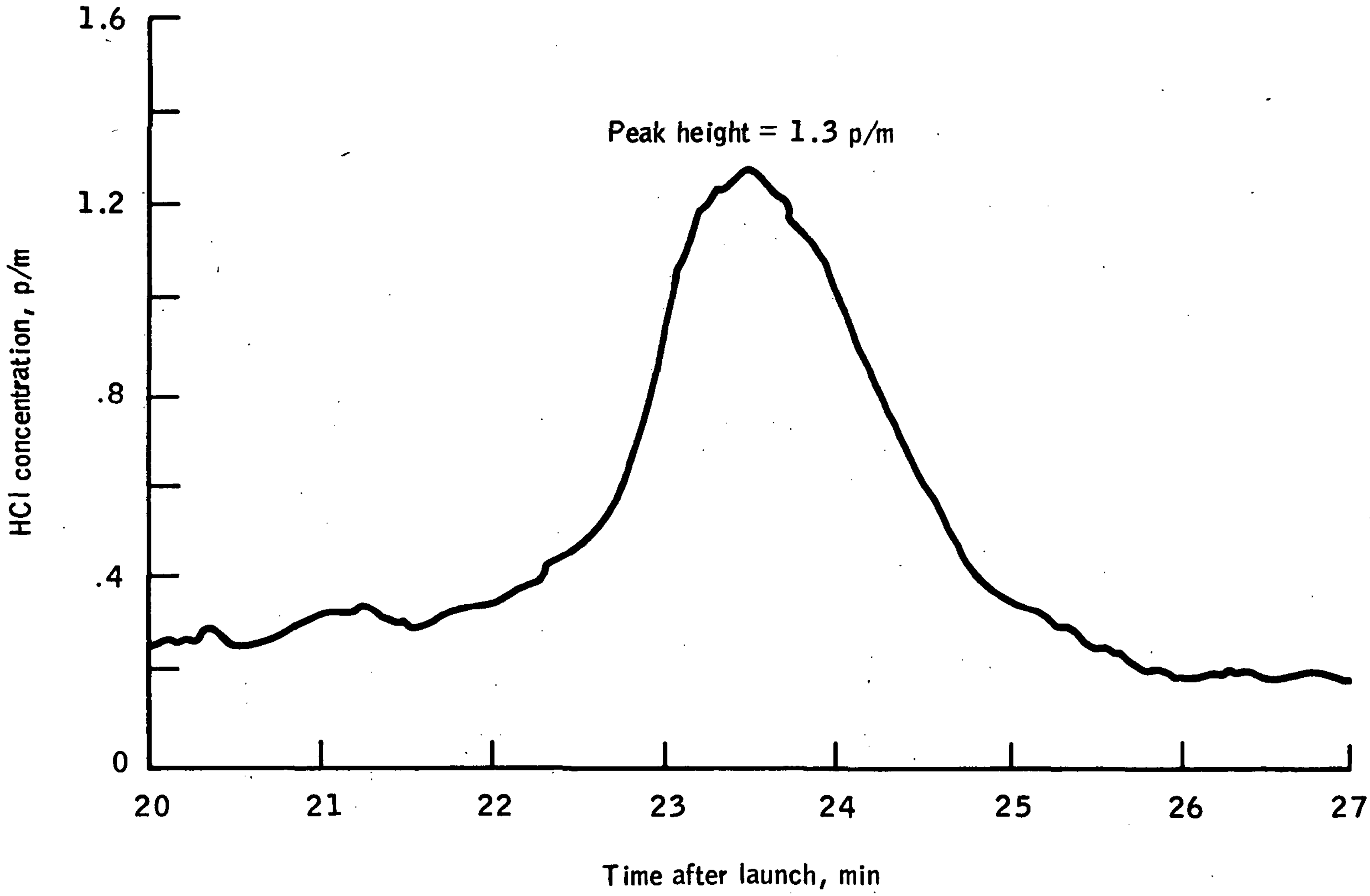


Figure C-9.- Peak hydrogen chloride (HCl) concentration observed after Titan III launch May 30, 1974 (5.2 kilometers downwind).

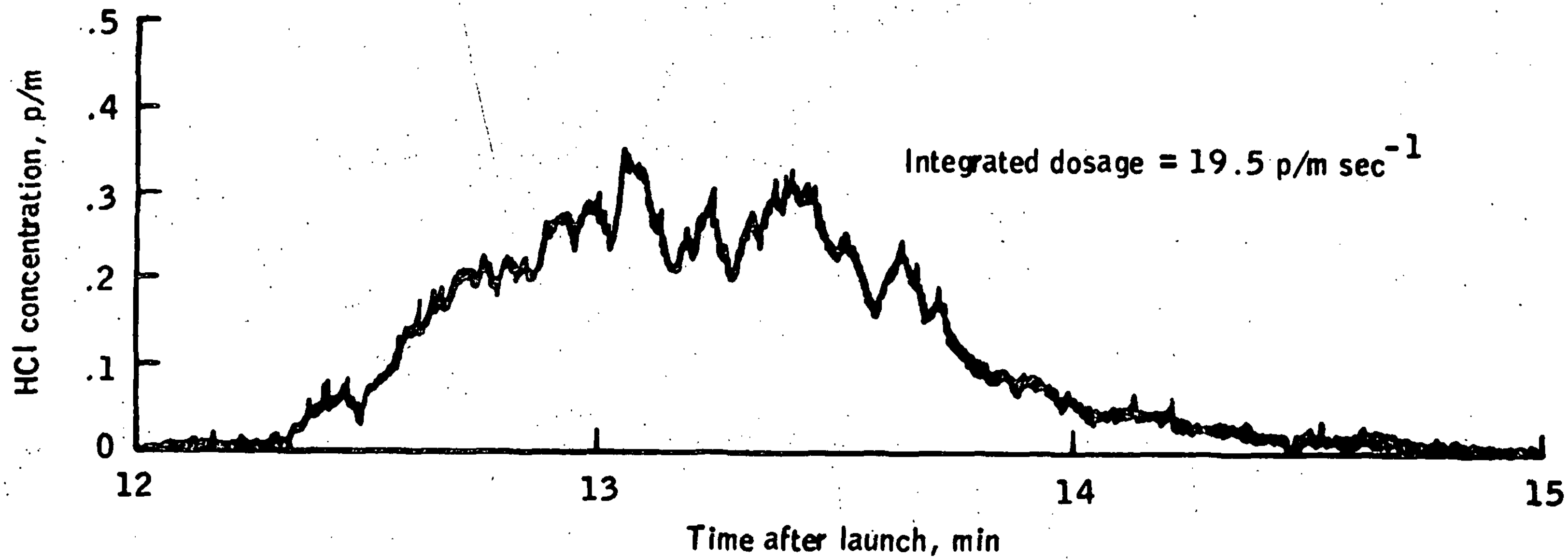


Figure C-10.- Peak hydrogen chloride (HCl) dosage observed after Titan III launch Dec. 10, 1974 (7.0 kilometers downwind).

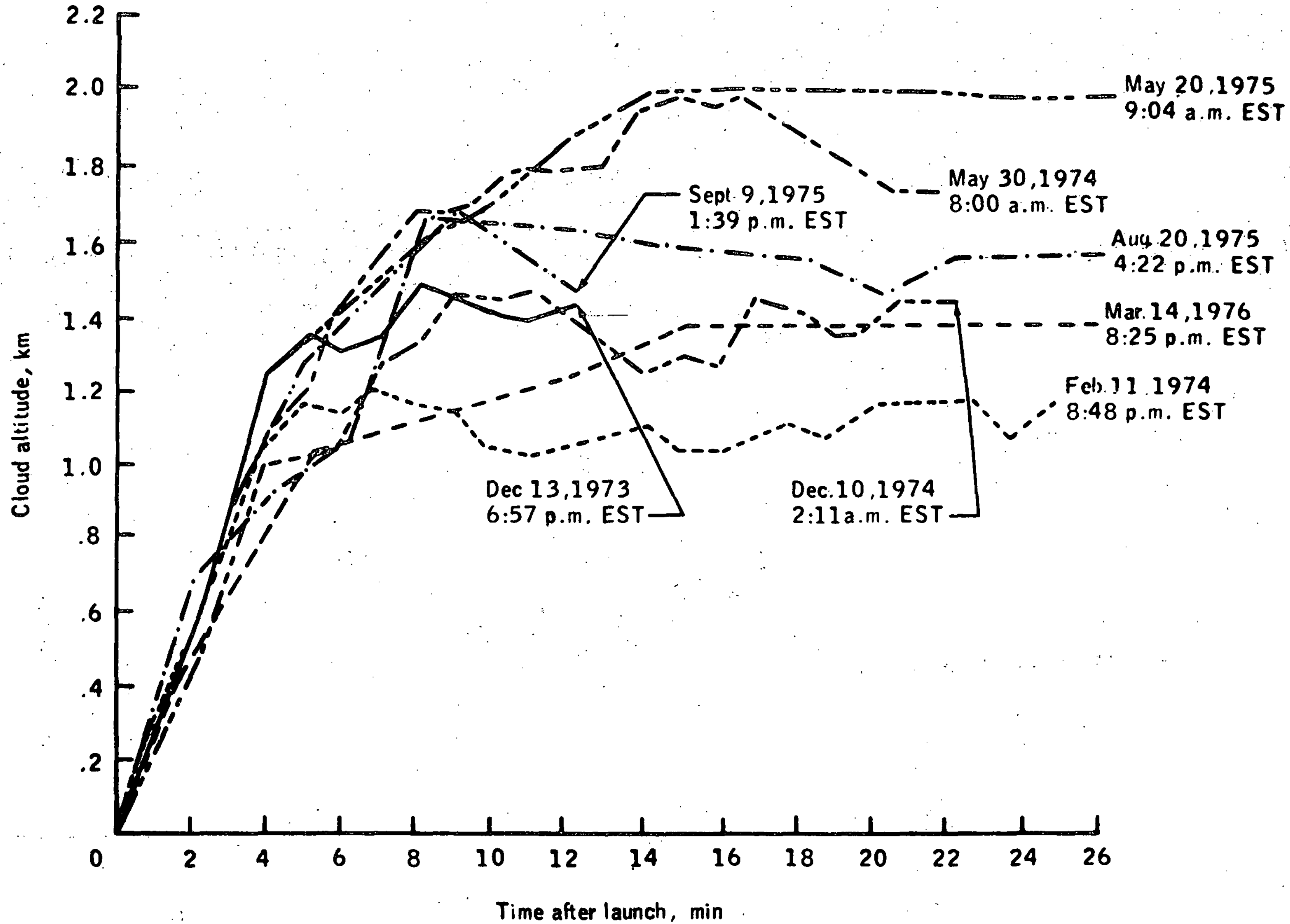


Figure C-11.- Cloud rise and stabilization heights in eight Titan III launches.

APPENDIX D - CLOUD TRAVEL

This appendix draws on material from two sources. It includes "Prediction of Cloud Transport," a brief report submitted at the workshop by G. L. Gregory of the NASA Langley Research Center (LaRC), and it includes "Future Activities for Improved Transport Predictions," excerpts of a workshop presentation by J. Briscoe Stephens of the NASA George C. Marshall Space Flight Center (MSFC). Tables and figures for all the material appear at the end of this appendix; one numbering system is used for both reports.

PREDICTION OF CLOUD TRANSPORT

Although not necessarily discussed in the 1972 Environmental Statement, the current state of the art in the prediction of ground-cloud trajectory should be remembered when discussing the NASA decision to develop launch constraints in the event of unfavorable environmental impact cases. Should the Shuttle launch effluents impact cause a more serious problem in which launches are frequently (or routinely) delayed because of air pollution considerations, then the following comments must be considered when addressing the launch constraint solution to the problem.

The major problem in prelaunch forecasting of the environmental impact of a solid rocket motor (SRM) may be cloud trajectory analysis. Assuming an accurate diffusion model, one must then forecast the trajectory of the cloud. The accuracy of this forecasted trajectory is somewhat dependent on the model (diffusion) accuracy, seriousness of the environmental impact, and the time period before launch when the decision is made.

During the seven previous Tital launches monitored, it has been observed that the meteorological inputs required by the existing effluent diffusion model can be reasonably forecasted 1 to 2 hours before launch under stable and well defined meteorology. Under these conditions, accuracy of trajectory might be approximately $\pm 10^{\circ}$. However, with the existing techniques and resources, meteorological forecasting (with the detail and accuracy required by the model) 4 to 6 hours before launch has been difficult even under stable meteorological conditions. In some cases, 4 to 6 hours forecasting of the quadrant of the cloud trajectory has been difficult. Under changing meteorological conditions (e.g., fronts passing through, onset of seabreeze, thunder storms), the problem is magnified.

It is the opinion of the LaRC staff involved that the forecasting tools used by MSFC during the last four Titan firings (see table C-I in appendix C) were the only ones available, considering the present launch constraints on meteorological soundings in the vicinity of the launch pad.

Forecasting these cloud trajectories was approached in a reasonable and professional manner; thus, the preceding comments on trajectory forecasting accuracies may be realistic. Some of the tools used in these forecasts were

1. Operational forecasting meteorologist

2. Synoptic data from the National Weather Service

3. Thermodynamic and kinematic data from the Air Force Eastern Testing Range (AFETR) weather information network display system (WINDS)

4. Local rawinsonde releases

5. Local tetroon releases

6. Weather station data from surrounding areas

7. Consultation with two or more meteorologists

The above comments are not intended to indicate that the cloud trajectory forecasting problem is unsolvable. Current efforts are underway by both the NASA John F. Kennedy Space Center (KSC) and MSFC to develop a meteorological forecasting model (or technique) for use during Shuttle operations. These studies will certainly refine some of the approaches used during the recent launch vehicle effluent (LVE) activities and hopefully develop new approaches. However, in preparation of Environmental Statement drafts, one must be aware of the current state of the art in trajectory forecasting, because there are no guarantees of improvement in the near future.

FUTURE ACTIVITIES FOR IMPROVED TRANSPORT PREDICTIONS

(PRESENTATION EXCERPTS)

There are two approaches that may be used in improving cloud transport predictions: data acquisition can be improved and predictive techniques can be improved. Data acquisition can be improved through use of more sounding locations (which would entail a mobile system with a 50-kilometer range), through use of tetroonsondes (which would require supporting investigations), and through use of remote sensing (which would require supporting investigations). Predictive techniques can be improved through development of a mesoscale model and through investigation of land-sea breeze effects.

The accuracy of present predictive capabilities is illustrated in table D-I. Figure D-1 illustrates percentages for cloud transportation in various directions.

TABLE D-I.- PREDICTION OF EXHAUST GROUND CLOUD TRANSPORT

(a) Prediction data

Time	Success of Eulerian forecast within 20° sector, percent	Best resolution, deg	Recommended evaluation technique
[a]T-24	25	90	Statistical
T-12	50	60	Statistical
T-8	70	40	Statistical determinist
T-4	80	30	Determinist statistical
T-2	90	30	Determinist sounding
T-0	96 (model)		Sounding

[a]T-24 means 24 hours before lift-off.

(b) Time of day relative to forecast success

Forecast time	Rating
Morning	Difficult
Afternoon	Reasonable
Evening	Difficult
Night	Reasonable

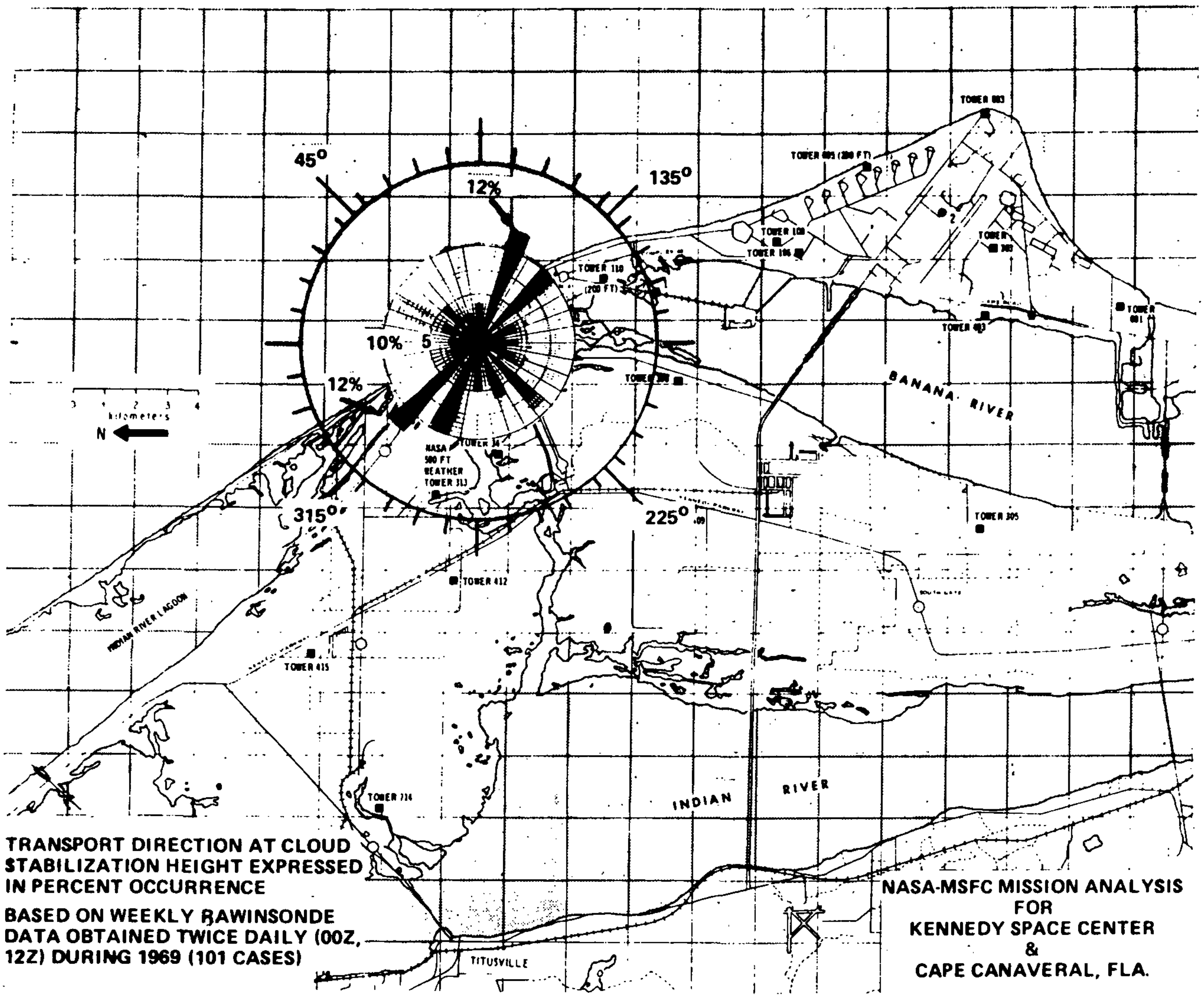


Figure D-1.- Transport direction at cloud stabilization height expressed in percent occurrence as related to the vicinity of the NASA John F. Kennedy Space Center. (Based on rawinsonde data obtained during 1969.)

APPENDIX E - ACIDIC RAINFALL

This appendix consists of three work-in-progress reports submitted to the workshop.

1. "Acid Rain," by G. L. Gregory of the NASA Langley Research Center (LaRC)

2. "Precipitation Scavenging of Hydrogen Chloride," by G. L. Pellett of LaRC

3. "Chemical Characteristics and Role of Aluminum Oxide in Shuttle Rocket Motor Exhaust Clouds," by W. R. Coffer, III, and G. L. Pellett, both of LaRC

References and figures for this group of reports appears at the end of the appendix; a single numbering system is used for all the reports.

ACID RAIN

In a revision of the 1972 Environmental Statement, modifications should be made to statements such as the following: "Standard operational procedures have been adopted that defer launches if weather conditions are such that the predictions of exhaust cloud concentrations, movements, and weather indicate unacceptable conditions." (See 1972 Environmental Statement, p. 16.) At the NASA John F. Kennedy Space Center (KSC) and the Air Force Eastern Testing Range (AFETR), there are no launch constraints based on environmental concerns. Vandenberg Air Force Base does have these launch constraints, although probably not as strong as the Environmental Statement suggests.

As the current Environmental Statement suggests, rain is probably the major problem associated with a Shuttle launch. This problem is more than a theory, because, during the September 9, 1975, launch at KSC, the ground cloud did intersect a rain cloud, and acid rainwater samples were collected in situ. Preliminary analyses of the data indicate that a large convective storm, moving in a westerly direction, intercepted the solid rocket motor (SRM) exhaust cloud about 12 to 15 minutes after launch, at approximately 2.5 kilometers from the launch site. Chlorine (Cl^-) analyses of rain samples, collected during the first hour at site locations within a 5- by 5-kilometer area indicated $p(Cl^-)$ from 1 to 3 (3550 p/m to 35 p/m Cl^-).

Rain collections at the two locations with the strongest concentrations were found to have $p(Cl^-)$ values near unity. These results, in conjunction with other data, appear to characterize a region of at least 1 square kilometer in which $p(Cl^-) < 1$. Deployment of pH papers and chemiluminescent hydrogen chloride (HCl) detectors at the same locations substantiate the strong-concentration areas. These pH papers showed extensive raindrop spotting, with most color changes indicating pH's of unity. Additional analytical and experimental information on the September 9, 1975, SRM rain scavenging event are still being analyzed. However, comparisons of $p(Cl^-)$ with available predictions of rain pH, for close-in Titan III SRM clouds dispersing under a variety of standard meteorological conditions, suggest that observed values of rain $p(Cl^-)$ and pH along the apparent centroid path are in reasonable agreement.

PRECIPITATION SCAVENGING OF HYDROGEN CHLORIDE

The Environmental Statement for the Space Shuttle Program (July 1972) states that "...For the (predicted) overland trajectories of the exhaust cloud, the possible harmful effects of rain containing HCl will be analyzed prior to each firing." "If the calculations predict unfavorable conditions, the launch will be postponed." The current assessment of the precipitation scavenging problem continues to support (1) the stated concern for possible harmful effects resulting from high acidities and total acidic ground depositions and (2) the need for continued efforts to achieve satisfactory implementation of the stated strategy.

The basis of the current preliminary assessment consists of the following:

1. Calculations of rain acidity and total HCl ground deposition, derived by application of a gaseous hydrogen chloride, HCl(g), scavenging model to calculated SRM cloud concentration histories (from a Gaussian dispersion model) for seven standard meteorological conditions (fig. E-1)

2. Experimental scavenging results obtained from chamber test firings conducted by the Illinois Institute of Technology Research Institute (IITRI)

3. Recent results obtained from field sampling experiments at KSC during the September 9, 1975, launch of Titan III C (Viking B)

Modeling Studies

The idealized HCl(g) scavenging model (developed at LaRC) simulates cases of independently generated vertical rainfall that overrides an independently dispersing SRM exhaust cloud. The model applies strictly at low to moderate humidities and under stable stratification conditions in the lower troposphere. Current grant and in-house efforts are aimed at developing improved scavenging models for two types of conditions:

1. High relative humidity conditions, where significant acid aerosol coexists with correspondingly reduced HCl(g) concentrations

2. Metastable to unstable atmospheric conditions, where convective interactions may become important or even dominant

However, preliminary findings of these studies are not yet available.

Predictions obtained from the idealized (LaRC) model, using as input the model 4, version II[1] multilayer diffusion concentration histories (layer centroid concentrations integrated in vertical direction), have continued to indicate that potential rain pH's of 2 or less and potential HCl ground depositions exceeding 2 g/m^2 per launch may occur, under some meteorological conditions, at distances greater than 200 kilometers. The dispersive decay of vertical HCl column density with distance from launch site (ref. E-1), which determines potential rain pH, appears to differ greatly among the seven "standard" meteorological regimes, spanning a range of two orders of magnitude at 100 kilometers from the launch site (fig. E-2).

Experimental Chamber Studies

Experimental scavenging results were recently obtained by IITRI from a limited set of chamber test firings of small SRM's. Estimated effective washout coefficients for total chloride were approximately 50 percent of those predicted by the classical Frössling correlation for absorption of HCl(g) by 0.9 millimeter droplets at terminal velocity. However, independent studies conducted at LaRC previously confirmed that the Frössling correlation was accurate within ±10 percent, under a variety of conditions, for 3-millimeter droplets falling in pure gaseous hydrogen chloride and nitrogen ($HCl(g)/N_2$) mixtures.

A plausible explanation of the 50 percent difference between these results is apparent. Field measurements and laboratory calibrations conducted by LaRC strongly suggest that the IITRI bubblers used to determine "chamber HCl(g) concentrations" also collected and measured chloride due to chlorided aluminum oxide (Al_2O_3) particles with attendent aqueous acid aerosol. Thus, it can be argued that the IITRI total-chloride scavenging results are reasonably consistent with the sum of two interdependent quantities:

1. Scavenging rates for HCl(g) at systematically reduced concentrations (because of gas to particle conversion), which are consistent with the Frössling correlation

2. Scavenging rates (efficiencies) for chlorided Al_2O_3/acid aerosol particles that are approximately an order of magnitude lower

The latter rates are in accordance with existing literature on aerosol scavenging, as reflected by IITRI's original expectations.

---

[1]Developed at George C. Marshall Space Flight Center (MSFC).

Finally, it should be noted that the air to exhaust weight ratio (A/E) in the IITRI experiments was only $\approx$225 in most cases. Thus, the operative aerosol growth kinetics in this case should deviate quite substantially from aerosol growth in "normal" unconfined SRM cloud expansions; e.g., where A/E ratios should exceed 10^4 after 3 to 5 minutes, and increase to $>10^5$ during the first half hour.

Field Studies

Recent results from LaRC field sampling experiments at KSC, during the September 9, 1975, launch of Viking B, represent the first documented and experimentally studied precipitation scavenging event in connection with an SRM launch. Details of the study are given in the section entitled "Acid Rain," which also gives the results of a preliminary Cl^- analysis.

During this study, rainwater chloride data from all eight primary sites were used to construct best-fit isopleths (fig. E-3) for $p(Cl^-)$. These isopleths indicated that a region of more than 30 square kilometers received rain of $p(Cl^-) \leq 3$. Since background levels of rainwater chloride, due to scavenging of sea salt aerosol, are normally much less than 1 p/m Cl^- (10 to 100 times), it is provisionally assumed that $p(Cl^-)$ is approximately "initial pH" for all eight sites until confirmatory sodium-ion-concentration measurements of $p(Na^+)$ are obtained. It appears likely that subsequent elevation of the "initial pH" occurs to some extent, due to reaction and dissolution of the scavenged Al_2O_3 particles. This effect may preclude or at least reduce the validity of direct pH measurements if they are made several hours or days after the scavenging event.

Additional analytical and experimental data on the September 9, 1975, SRM exhaust cloud size and spatial concentration history are still being analyzed. However, comparisons of $p(Cl^-)$ with available predictions of rain pH, for close-in Titan III C SRM clouds dispersing under a variety of standard meteorological conditions, suggest that observed values for rain $p(Cl^-)$ and pH along the apparent centroid path are in reasonable agreement with expectations.

Development of Accurate Predictive Schemes

A reasonably complete resolution of the HCl partitioning/precipitation scavenging problem, which should enable satisfactory predictions of acid rain for the high humidity conditions and diverse weather patterns characteristically encountered at KSC, will require a combination of task efforts. Some of the more important tasks, most of which are either planned or ongoing, are as follows:

1. Further chamber firing tests that are more completely instrumented (e.g., inclusion of HCl(g) monitoring capability by gas filter correlation technique)

2. Achievement of substantially larger A/E ratios in selected chamber tests

3. Continued in situ aircraft sampling of SRM exhaust clouds, adding a gas filter correlation analyzer for HCl(g) and a gas chromatographic (electron capture) system for sulfur hexafluoride (SF_6) tracer studies

4. Establishment of a suitable rain sampling network at KSC

5. Continued study of $HCl/H_2O/Al_2O_3$ chemisorption and microchemistry in both gas-solid and aqueous systems

6. Continued development of computational methods that treat the essential microphysics and resultant scavenging for a variety of anticipated atmospheric conditions

7. Adoption of improved computational methods for the prediction of SRM cloud dispersion

8. Development of methodology for more accurate predictions of local meteorology

CHEMICAL CHARACTERISTICS AND ROLE OF Al_2O_3 IN SRM EXHAUST CLOUDS

Available evidence indicates that a major proportion of the alumina emitted by an SRM consists of small-particle-size ($0.01 < d < 1$ micrometer) metastable crystalline Al_2O_3. Amorphous aluminum oxides may also coexist with crystalline phases, but the percentage has not yet been estimated. Metastable aluminas, in contrast to the stable and relatively inert alpha crystalline form, exhibit a significant degree and range of surface reactivity and solubility.

The current assessment of the chemical characteristics of Al_2O_3 in SRM clouds focuses primarily on effects that result from the interaction of metastable aluminas with HCl and H_2O in both gaseous and liquid phases. The investigators provisionally conclude that the available (to gas) particle surface area soon becomes nearly covered, with one to several molecular layers of hydrated surface chloride, in various chlorine bonding states, as the result of HCl(g) + H_2O(g) sorption with subsequent reaction. The resultant chlorided Al_2O_3 surface has altered hygroscopic and acidic properties, as well as solubility behavior, that appear to have direct influences on acid aerosol formation (heteromolecular condensation) and H_2O and HCl vapor pressures in subsequent solution. The latter vapor pressure perturbations in turn will affect the processes of aqueous aerosol growth and evaporation. Since precipitation scavenging efficiencies are very strongly dependent on aerosol size distribution, the above microchemical deviations from the idealized case (pure HCl/H_2O

aerosol on inert Al_2O_3 particles) may have a significant effect on acid rain predictions. Finally, the acidic chlorided surface of the Al_2O_3 particles may have a dominant role in the damage mechanisms on various ground-receiver surfaces.

Although much work remains to derive explicit quantitative relations that will approximate the microchemical perturbations (for use in a precipitation scavenging model), the following discussion of $HC/H_2O/Al_2O_3$ interactions basically summarizes the investigators' current understanding.

A small fraction of the total SRM HCl ($\leq$6 percent) is predicted to react with, and partially chloride, the surfaces of numerous metastable Al_2O_3 particles ($0.01 < d < 2$ micrometers) in the plume — at temperatures below 1000 K and in the "dry" aerosol condition. This assessment is based on results from

1. Recent measurements of significant surface chloride formation, after short exposure (7 seconds) of gamma crystalline form aluminum oxide (γ-Al_2O_3) to a fuel-rich propane-air flame containing 5 percent HCl

2. Longer duration, ambient-temperature chemisorptions of dilute HCl + H_2O gas on metastable Al_2O_3 (discussed later), including chloride analyses of both lab-chemisorbed and SRM-produced (tank firings) Al_2O_3 samples

3. Review of previous HCl/Al_2O_3 reaction studies

It should be noted that significantly more HCl may react with the alumina if a liquid HCl/H_2O phase (acid aerosol) should form around the Al_2O_3 particulates.

Although the use of vapor pressure data for the pure HCl/H_2O system may be adequate for initial assessments of aerosol formation and growth, recent studies of $Al_2O_3/HCl/H_2O$ interactions in the laboratory and at William and Mary College have indicated that some transient vapor pressure corrections are needed to account for the effects of soluble aluminum-containing ions.

The investigators have evidence that chemisorption of gaseous HCl + H_2O (35, 80, and 300 p/m HCl) in N_2 at 75-percent H_2O saturation on metastable Al_2O_3 forms a "hydrated surface chloride," which appears to develop enhanced hygroscopicity as the reaction proceeds to significant surface coverage during the first 0.5 hour. Quasi-equilibrium coverage of hydrated surface chloride, attained after several hours, is equivalent to $\approx$0.8 mg/m^2.

The rate of HCl and H_2O gas uptake (physically and chemically sorbed) in the experiments on metastable aluminas to date, has been predominately controlled by the surface area of the particulates. (See figure E-4.) The surface chloride subsequently is 100 percent soluble in water and can be titrated quantitatively with Ag^+. A similar statement, with some reservations, applied to dissolution of aluminum from the adsorbent. Approximately 1 mole of aluminum is dissolved for every 3 moles of Cl^-, but the ratio appears to vary somewhat with chemisorption conditions. Although the nature of the major aluminum-containing ions has not been determined, it seems reasonable to postulate a positively charged aluminum hydroxide species ($Al(OH_2)_6^{3+}$) at $pH < 2$, and generalized aluminum oxychlorides at $pH > 2$; i.e., $[Al_x(OH)_y(OH)_y(OH_2)_z]^{(3x - y)^+}$, $(3x - y)Cl^-$.

When metastable alumina contacts aqueous HCl, the rate of surface reaction appears to be significantly faster than in the case of chemisorption; quite obviously, ionic species dominate solution behavior, and the extent of reaction is influenced by dissolution of the solid, which occurs simultaneously.

Results from recent isopiestic quasi-equilibrium experiments indicated that dissolution of metastable Al_2O_3, by 10 percent by weight HCl at 303 K (30° C), led to significant weight loss, due mainly to H_2O evaporation, after various samples (in open weighing bottles) were allowed to exchange volatile components with a 10 percent by weight HCl bath solution for 9 to 12 days. Net evaporative loss of H_2O increased significantly with initial Al_2O_3/HCl-solution weight ratio, which ranged from 0.06 to 0.95.

Further study by S. Y. Tyree at the College of William and Mary (refs. E-2 and E-3) on metastable Al_2O_3/HCl solutions (fig. E-5), using a vapor pressure osmometer technique, has not only confirmed that alumina will enhance evaporation of H_2O from HCl solutions, but in time frames appropriate to anticipated conditions (<20 minutes).

Thus, although many important details of the $Al_2O_3/HCl/H_2O$ interaction in an SRM cloud are not presently understood, it seems clear that

1. Chemisorption of $HCl(g) + H_2O(g)$, at temperatures below 1000 K, will form hydrated chlorine-containing compounds on the Al_2O_3 surface, which tend to initially increase surface hygroscopicity.

2. The rate and extent of chemisorption will depend on the surface area of the alumina, exhaust dilution/temperature-decay history, air temperature, and relative humidity.

3. Formation of an aqueous acid phase (if it occurs) will be accompanied simultaneously by leaching of chlorine- and aluminum-containing species from the preexisting chemisorbed phase that will likely react at $pH > 2$ to produce aluminum oxychlorides. Formation of aluminum oxychlorides will likely produce an increased H_2O vapor pressure over the aerosol droplet, thereby retarding growth, in comparison to the idealized "non-reactive solid" case.

REFERENCES

E-1. Knutson, Earl O.; and Fenton, Donald L.: Atmospheric Scavenging of Hydrochloric Acid. NASA CR-2598, 1975.

E-2. Tyree, S. Y.: Chemistry of the System Al_2O_3(c) - HCl(aq) Status Report. NASA CR-146309, 1975.

E-3. Tyree, S. Y.: Chemistry of the System Al_2O_3(c) - HCl(aq) Status Report. NASA CR-146728, 1976.

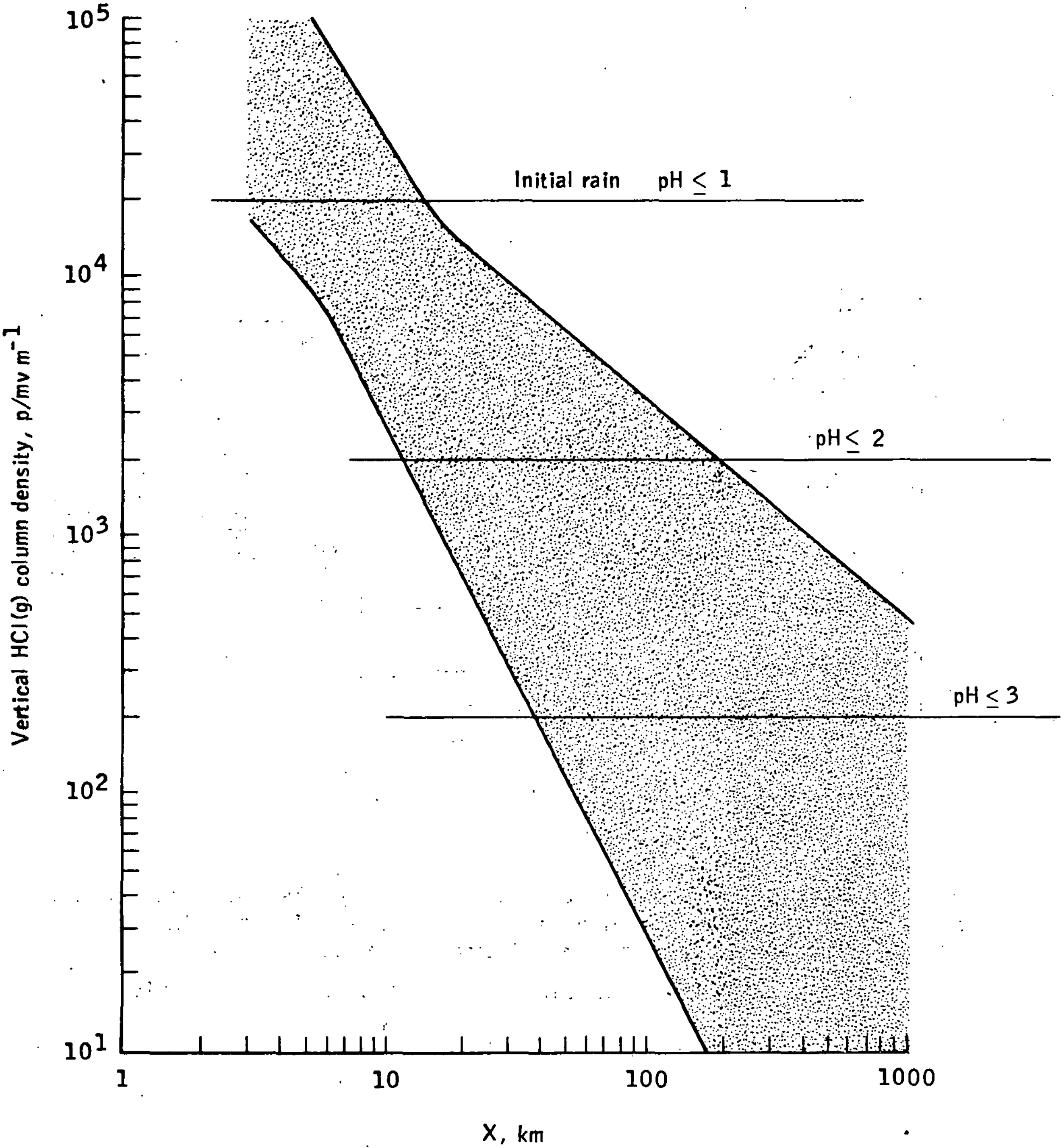


Figure E-1.- Predicted decay acid rain potential envelope for seven standard meteorologies using Titan III C launches. ($X = X_{cs} + X_0$; where X_{cs} is the distance from launch site to cloud stabilization or zero point, and X_0 is the distance from X_{cs} to the event.)

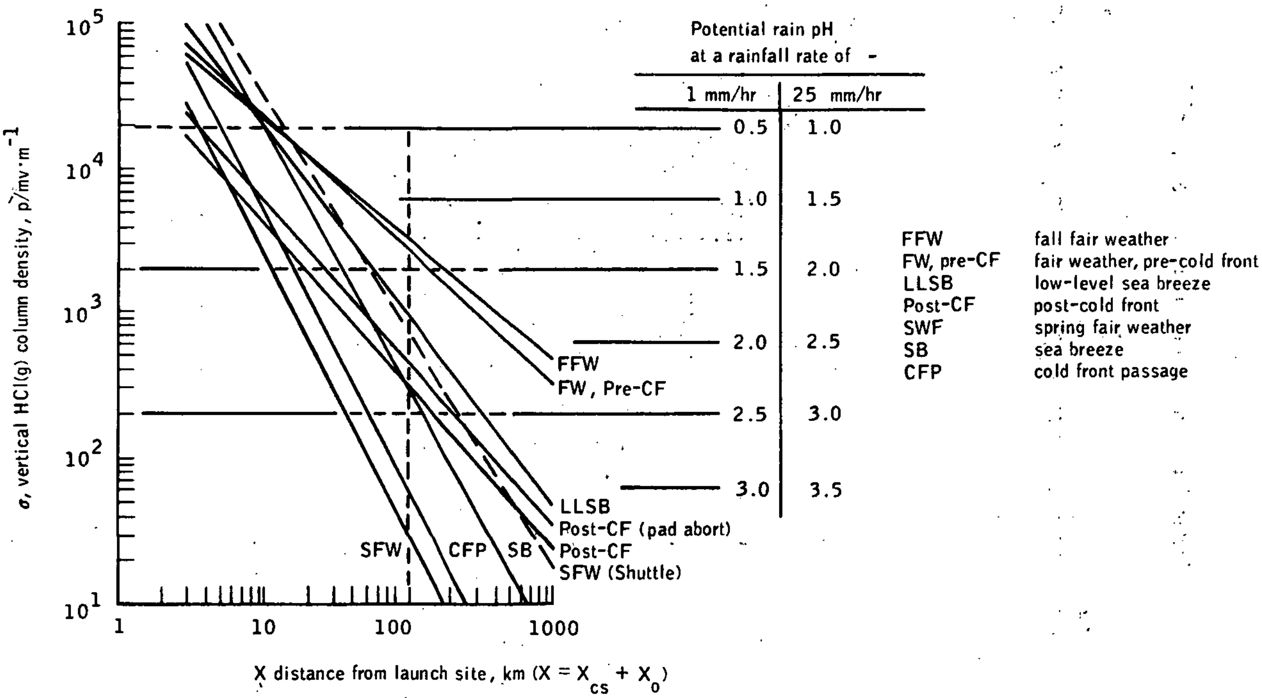


Figure E-2.- Predicted decays of acid rain potentials for seven standard meteorologies (derived from model 4, version II of the NASA George C. Marshall Space Flight Center multilayer diffusion model). ($X = X_{cs} + X_0$; where X_{cs} is distance from launch site to cloud stabilization or zero point, and X_0 is distance from X_{cs} to the event.)

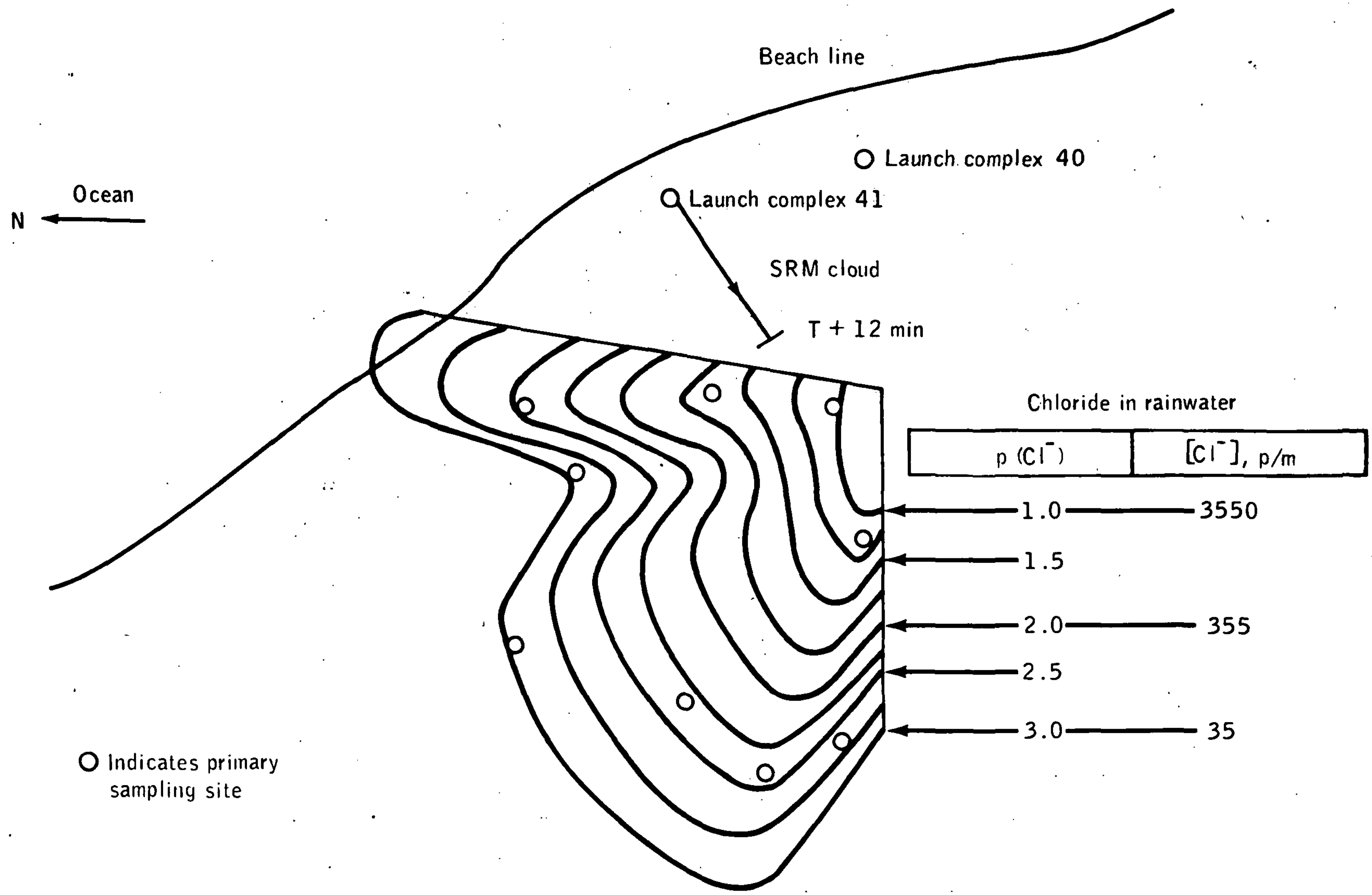


Figure E-3.- Acid chloride footprint from precipitation scavenging of Titan III C SRM exhaust cloud from Viking B launch on September 9, 1975.

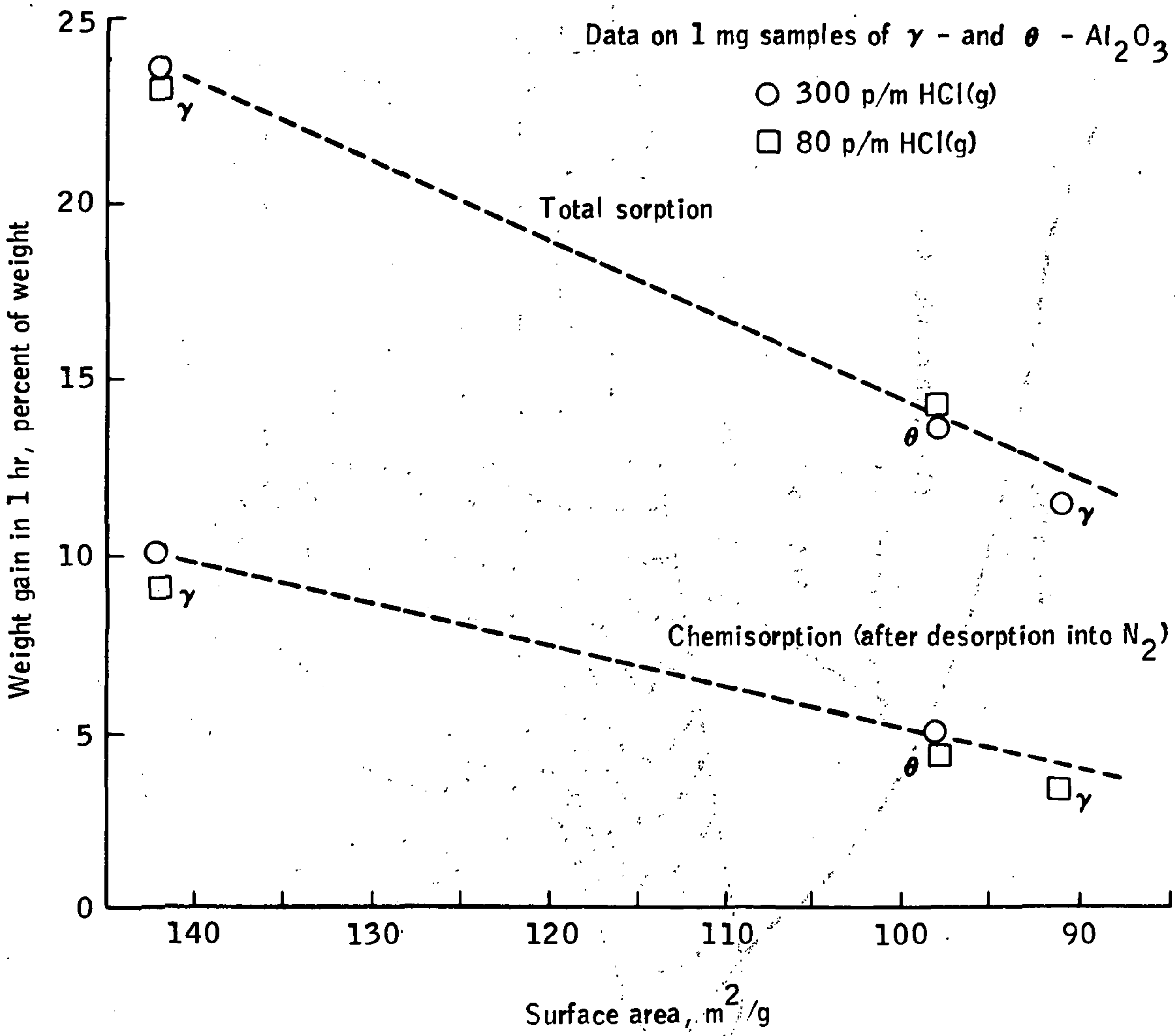


Figure E-4.- Influence of aluminum oxide surface area, metastable crystalline phase, and HCl(g) concentration on adsorption of dilute HCl(g) + $H_2O(g)$ mixtures at 75-percent vapor saturation.

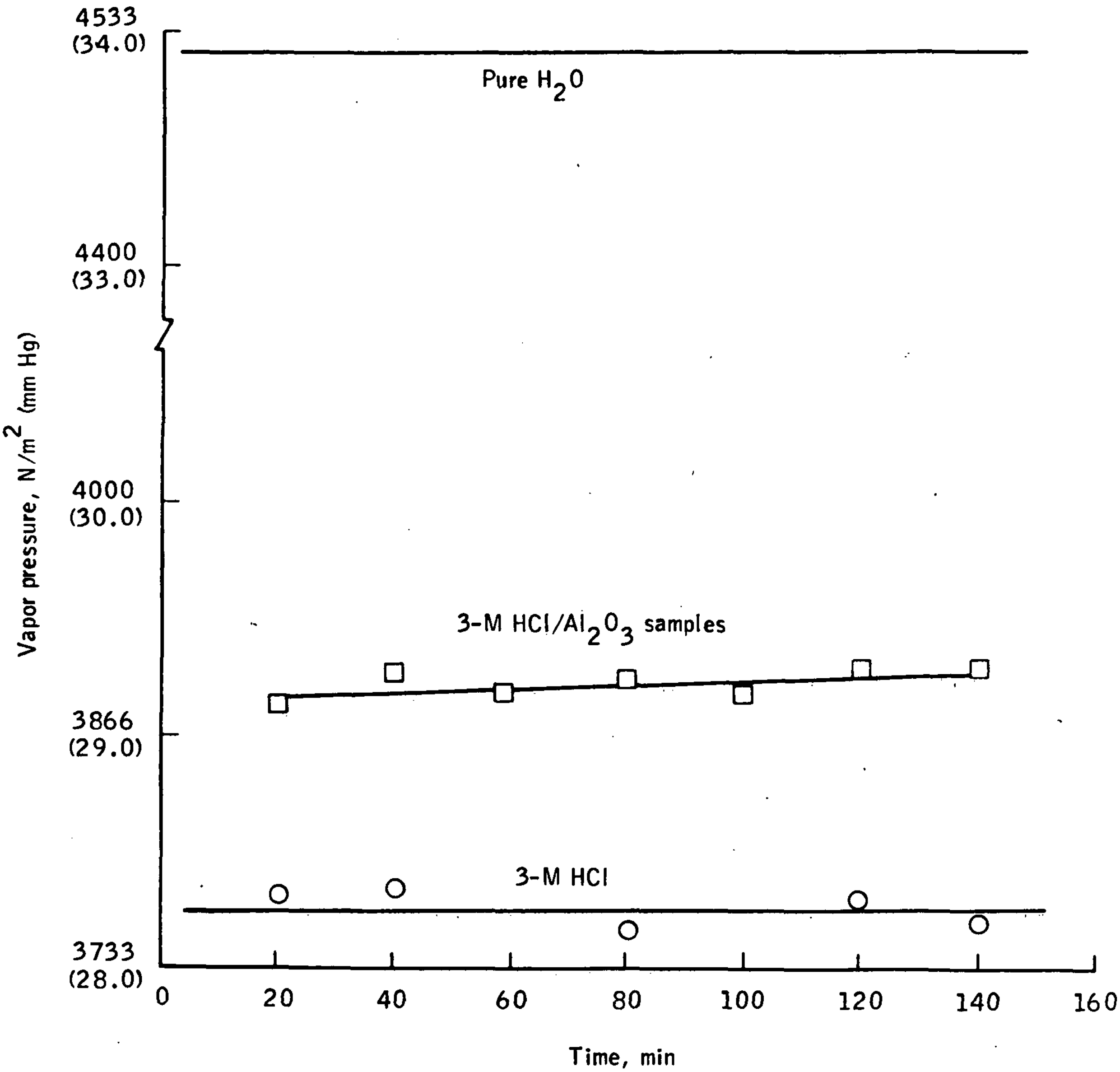


Figure E-5.- Effect of partial aluminum oxide dissolution in 3-molar aqueous hydrogen chloride on total vapor pressure. (T = 304.2 K (31.0° C).)

APPENDIX F — SONIC BOOM AND LAUNCH NOISE

This appendix consists of material from three sources.

1. "Sonic Boom Activities," excerpts from a workshop presentation by F. Garcia of the NASA Lyndon B. Johnson Space Center (JSC)

2. "Review of Environmental Protection Agency Environmental Noise Level Documents," a memorandum (revised Nov. 21, 1974) from E. E. Rice and A. E. Waller of the Battelle Columbus Laboratories

3. "Launch Noise," a workshop presentation by the John F. Kennedy Space Center (KSC) staff

A single number system is used for references, tables, and figures in the three papers.

SONIC BOOM ACTIVITIES (PRESENTATION EXCERPTS)

A number of research analyses regarding Space Shuttle sonic booms have been completed or scheduled. The JSC schedule of sonic boom activities is shown in table F-I.

The first operational test flight (OFT-1) will use the Mission Planning and Analysis Division nominal entry from orbit 21 (fig. F-1, table F-II). The entry starts with an angle of attack α of 40°. This swiftly changes to $\alpha = 30°$. Thereafter, there is a gradual change to $\alpha = 13°$ starting at approximately 3200 m/sec (10 500 ft/sec). This angle is maintained until velocity has decreased to approximately 762 m/sec (2500 ft/sec). Thereafter, the angle of attack is variable, depending upon the switch point state.

The interface between entry and terminal area energy management occurs at a height of approximately 25 300 meters (83 000 feet). Land overflight begins at Mach 5.6.

REVIEW OF ENVIRONMENTAL PROTECTION AGENCY ENVIRONMENTAL NOISE LEVEL DOCUMENTS (COPY OF MEMORANDUM)

At the request of Mr. J. W. Haughey, NASA Launch Vehicle and Propulsion Programs, the Environmental Protection Agency (EPA) draft instruction manual entitled: "An Instruction Manual for General Utilization of the EPA Document (550/9-74-004) Identifying Acceptable Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety" (BMI-NLVP-Lib. No. 74-421) and the EPA document entitled "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety (550/9-74-004)" (BMI-NLVP-Lib. No. 74-422) were reviewed. Hereafter, the first document will be referred to as the "draft manual", and the second will be referred to as the "levels document."

Background

The Noise Control Act (NCA) of 1972 stipulates that the EPA has the responsibility of publishing several documents relating to noise in the environment. The materials reviewed here are in response to the NCA stipulations.

The two EPA documents define a noise descriptor and present preliminary noise guidelines that will likely be used in establishing future noise standards and regulations. The 1972 NCA states that noise regulations and standards are the responsibility of state and local governments. The information provided in the EPA documents is meant to be used in the preparation of state and local noise regulations.

The relatively new noise descriptor involves the use of an "equivalent A-weighted sound level (L_{eq})." The equivalent A-weighted sound level is the constant sound level that conveys the same A-weighted sound energy as the actual time-varying A-weighted sound; L_{eq} is mathematically defined as

$$L_{eq} = 10 \log_{10}\left(\frac{1}{T}\int_0^T 10^{\frac{L(t)}{10}}\,dt\right) \qquad \text{(F-1)}$$

where $L(t)$ is the A-weighted sound level (dB) existing between $t = 0$ and $t = T$. If L is not available in functional form, the following equation is used

$$L_{eq} = 10 \log_{10}\left(\sum_{i=1}^{i=n} X_i\, 10^{\frac{L_i}{10}}\right) \qquad \text{(F-2)}$$

where X_i is the fraction of the total time in which the A-weighted sound level, L_i, occurs. For example, if $L_1 = 110$ dB(A) for

$$X_1 = \frac{120 \text{ sec}}{86400 \text{ sec } (=24 \text{ hr})} \quad \text{(F-3)}$$

and $L_2 = 50$ dB(A)(background) for $X_2 = 1 - X_1$, then $L_{eq(24)} = 81.4$ dB(A).

The cumulative noise level chosen as a guideline ($L_{eq(24)}$) was derived based upon hearing losses for 4 percent of the population as incurred over a 40-year period at $L_{eq(8)} = 75$ dB(A) for an 8-hour industrial situation. A value of $L_{eq(8)} = 75$ dB(A) is equivalent to $L_{eq(24)} = 70$ dB(A) when 16 hours remaining are at 60 dB(A) or lower. For any noise occurring between the hours of 10 p.m. at night and 7 a.m. in the morning, a 10 dB(A) penalty is to be added to all sound levels.

Throughout the EPA documents, it is stated that no consideration was given to feasibility or cost in establishing the suggested guidelines; EPA also reminds the reader that the guidelines presented should not be construed to be federal standards. The EPA does suggest that other federal agencies adopt the L_{eq} noise descriptor, especially when preparing environmental statements.

Regarding Launch Vehicles

The "levels document" refers to two basic noise measures; they are -

1. Cumulative measures based upon an "A" weighted L_{eq}

2. Discrete measures based upon the maximum "D" or "A" weighted sound levels (impulse and other special noise)[1]

For a given 24-hour period, the daytime launch of a Titan Centaur, Atlas Centaur, or Delta would probably exceed the guideline of $L_{eq(24)} = 70$ dB by about 10 dB (A weighted), at the various boundaries of KSC. However, if the noise levels are averaged over an entire year for typical launch activities (5 Titans, 5 Atlas Centaurs, and 10 Deltas) with the assumption of a 60 dB background noise, the "A" weighted noise level would be ≈67 dB for the city of Cape Canaveral, which is below the $L_{eq(24)} = 70$ dB guideline. It is worth

---

[1]The "D" weighting is relatively new and is being evaluated for possible use by the EPA as a replacement for the "A" scale.

noting that the background contributes only 1 dB to the above L_{eq}; if all sound other than that from the launch vehicles would somehow be eliminated, the L_{eq} would still be 66 dB.

If it is assumed that half of the Delta launches occur at night, as is typical, then the L_{eq} rises to $\approx$72 dB, which is above the 70 dB guideline. Noise levels within the KSC boundaries would probably exceed the EPA guidelines ($L_{eq(8)}$ = 75 dB) for working personnel, even when all launches are averaged over the entire year.

Additional information or guidelines concerning measures based on the maximum "D" or "A" weighted scales (item 2) is required before an appropriate evaluation of the possible effects of "intermittent" launch vehicle noise on human hearing losses can be determined. Intermittent noise has been shown to be less damaging than continuous noise of the same L_{eq}, so perhaps other guidelines for noises occurring for short intervals should be included in the guidelines, preferably under the section "Impulse Noise and Some Other Special Noises."

Table F-III compares the permitted duration of various sound pressure levels using the EPA proposed criteria of L_{eq} = 70 dB(A), OSHA rules, and Kryter's first criteria. The table illustrates the extreme conservatism that is present in applying the EPA's L_{eq} descriptor for high intensity, intermittent noise of short duration.

The proposed EPA equivalent sound level L_{eq} defined as

$$L_{eq} = 10 \log_{10}\left(\frac{1}{T}\int_0^T 10^{\frac{L(t)}{10}}\,dt\right) \qquad \text{(F-4)}$$

where $L(t)$ is to be measured in dB(A), can be regarded as a specific case of the more general relation

$$D = 10a \log_{10}\left(\frac{1}{T}\int_0^T 10^{\frac{L(t)}{10a}}\,dt\right) \qquad \text{(F-5)}$$

Thus, when $a = 1$, $D = L_{eq}$, and L_{eq} is a measure of the total acoustic energy in the period T. The proposed L_{eq} for 24 hours of 70 dB(A) corresponds to an A-weighted acoustic energy "dose" of 86.4 microwatt-seconds/cm^2.

If a is assigned a value of 2, then D is a measure of the average acoustic pressure. The value of D for any specified value of a, D_a, represents an average sound pressure level for the interval T. If L(t) is a constant, then all D_a's will be equal, but the numerical values of D_a for different a's will diverge increasingly as L(t) departs from a constant.

In the past, most noise criteria appear to reflect a value of a more nearly equal to 2 than 1 (table F-III). For example, the OSHA industrial criteria (ref. F-1) correspond to a = 1.67, and Kryter's criteria for zero hearing impairment for normal speech in quiet surroundings (ref. F-2) correspond to a = 2.

As pointed out earlier, the value of a has an increasingly large effect on the average sound level as the instantaneous sound level increasingly departs from the average. Thus, when the EPA averaging procedure is applied to high intensity, short duration sound sources, such as launch vehicles, the result is a suprisingly high 24-hour average sound pressure level (SPL). Figure F-2 was constructed to illustrate this point. The equation used to construct the two plots (a = 1, and a = 2) in the figure is given as

$$D = 10a \log_{10}\left[X \cdot 10^{\frac{L_1}{10a}} + (1 - X) \cdot 10^{\frac{L_2}{10a}}\right] \qquad \text{(F-6)}$$

where L_1 = 110 dB(A), lasting for X fraction of a 24-hour day

L_2 = 60 dB(A), the assumed average background noise level for 1 - X fraction of the 24-hour day

As noted from figure F-2, the two curves (a = 1, and a = 2) approach each other for very short impulse noise (less than a second) and intersect each other for continuous noise levels (X = 1). There is a substantial difference between the two curves, for values of X less than 0.1 and greater than 10^{-4}. This difference should point out the need for study to determine whether averaged energy or averaged pressure should be used for intermittent noise. For the estimated duration and sound pressure level of a Delta launch, as heard in Cape Canaveral (closest KSC boundary), of 60 seconds and 110 dB(A), the difference between "energy" and "pressure" is quite evident. For the EPA averge energy descriptor method, a Delta launch exceeds the 70 dB(A) guideline. For the "pressure" averaged value of D, the Delta launch does not exceed the 70 dB(A) guideline.

The EPA indicates that once noise regulations and limits are adopted for a certain locale, special permits might be granted for such things as parades, sporting events, and the operation of certain equipment, provided the event has a certain beneficial social value. If launch vehicle operations were to cause noise levels that exceed future noise standards, then it is understood that perhaps a permit would be required before a vehicle launch. The nighttime penalty of ≈10 dB could place additional constraints on nighttime launch vehicle operation. If certain "local" groups were to protest the granting of such permits, launches might be delayed. This would undoubtedly create severe problems for planetary missions (day or night).

There is little that can be done to reduce noise resulting from the launch of space vehicles. Vehicle thrust, the number of engines, the weather conditions, and the location of the launch site appear to be the influencing factors upon the noise levels generated. The situation in the future is not likely to improve. When the Shuttle moves onto the scene, increased sound levels will be prevalent. For the Space Shuttle years; the increased thrust, the increased number of flights, and the presence of sonic booms will contribute to an increase in average noise levels that exist at KSC. The EPA does realize the problems involved in enforcing their suggested guideline by stating: "In most applications, however, for reasons of economics and/or technical feasibility the levels of the 'Levels Document' will necessarily be set higher initially."

The BMI-NLVP believes that the A-weighted L_{eq} may be a good method to evaluate semicontinuous noise levels; however, two points need to be emphasized regarding shorter term exposures, as experienced in space vehicle launches and other intermittent noises.

1. What is the proper threshold for short-term human exposures (20 to 120 seconds)?

2. Is hearing damage related to average total energy, average total pressure, or peak pressure effects, and do the damage criteria depend upon the duration of exposure?

Specific Comments on EPA Documents

In general, the "draft manual" could be improved by the inclusion of additional information, the elimination of certain sentences, the proper choice of words in several places, and a detailed review by an acoustics expert. Comments relating to the above are exemplified by the following:

1. The "D" and "A" weighting scales are referred to, but nowhere are they presented so that they can be applied to calculations. The "Levels Document" indicates that the weighting scales were presented in the "criteria document." The investigators believe that weighting curves, or tabular data should be presented in the "draft manual." Sound frequency weighting scales are shown in figure F-3 (ref. F-2).

2. An example of a rather weak statement is: "... but sound can only be eliminated by creating a vacuum - a condition in which humans cannot exist" (page 8).

3. On page 30, word choice appears to be a problem "... only a few microseconds - peak lasts only a few millionths of a second." On page 33, "planes" should be replaced by "aircraft."

4. The "acoustic" discussion on page 28 needs correcting.

In general, the "Levels Document" is in a good state except for the need for additional data concerning the "D" or "A" weighting and short term exposures to intermittent noises.

Recommendations

1. The NASA should supply the EPA with comments, especially regarding the need for short-term noise-exposure guidelines for times ranging, for example, from 20 to 120 seconds, and question the validity of total energy averaging as compared to "pressure" averaging.

2. Future NASA environmental statements should include (but only after the "energy" versus "pressure" issue is settled) the use of the L_{eq} descriptor and other EPA guidelines regarding short term or intermittent exposures.

3. At this time, no action should be taken regarding the noise section in the NASA/Office of Space Sciences (OSS) Environmental Statement for Launch Vehicle and Propulsion Programs.

4. Noise levels should be measured at JSC White Sands Test Facility, KSC, and Vandenberg to establish existing noise levels at the launch sites and at the boundaries. It is suggested that NASA Langley Research Center (LaRC) personnel make simple acoustic measurements while making effluent measurements during upcoming launches.

LAUNCH NOISE

There is a substantial area of possible sound-pressure-level/exposure-time between the 135-decibel pain limit for a given exposure and the 90-decibel Walsh-Healy-Act limit for continuous exposure.

The KSC must be prepared to control the acoustic effects of spaceport landings and launches. The landings are expected to be accompanied by sonic booms that can be controlled only by selection of a path of approach which confines this sonic boom to ocean areas. Launches require large buffer areas that are under the complete control of KSC for exclusion of the public and for enforcement of protection procedures relative to the remaining personnel.

The 110 decibels for 1 minute is selected as a reasonable decibels/exposure-time when applied to a 2.9×10^7 newton (6.6 million pound) thrust Shuttle launch. Table F-IV shows the decibel levels compared to distance from the center of the mobile launcher platform. Figure F-4 shows the 110-decibel line for the launch at a scale that can be overlaid on the KSC general area plan. Placement of this overlay on the existing and future launch areas and rotation of the launch azimuth will show the necessity for the limitations imposed by the present KSC boundaries.

REFERENCES

F-1. Federal Register, vol. 34, no. 96, p. 7949, May 20, 1969.

F-2. Kryter, K. D.: The Effects of Noise on Man. Academic Press, 1970.

TABLE F-I.- THE JSC SCHEDULE OF SONIC BOOM ACTIVITIES

Activity	Schedule
Modeling of launch configuration[a]	
Wind tunnel test data	Available Aug. 1, 1976
VAFB and KSC analysis[b]	Complete Oct. 1, 1976
Entry	
OFT-1	Completed
VAFB analysis	Available Aug. 1, 1976
Power spectral density analysis	Started Dec. 1, 1976
OFT-1 sonic boom Flight Test Program	
Inputs made via flight test requirements	Under consideration
Experiment proposal to Orbiter Experiments Program	Under consideration

[a]Launch configuration includes orbiter, external tanks, and plumes.

[b]VAFB is Vandenberg Air Force Base, KSC is the NASA John F. Kennedy Space Center.

TABLE F-II.- SONIC BOOM CHARACTERISTICS OF OFT-1

[Nominal OFT-1 return from orbit 21][a]

Mach number	Angle of attack, deg	Roll angle, deg	Altitude, m (ft)	Peak overpressure, N/m^2 (lb/ft^2)
4.06	17.4	-57.7	32 258 (105 833)	49.8 (1.04)
3.86	16.7	-48.4	31 327 (102 779)	53.6 (1.12)
3.66	16.1	-40.2	30 226 (99 167)	57.0 (1.19)
3.46	15.4	-36.3	29 119 (95 535)	60.3 (1.26)
3.28	14.8	-36.3	28 257 (92 708)	62.7 (1.31)
3.07	14.2	-36.3	27 302 (89 575)	66.1 (1.38)
2.89	13.6	-36.3	26 552 (87 114)	68.0 (1.42)
2.67	13.0	-35.8	25 698 (84 312)	70.4 (1.47)
-------	-------	-------	-------	-------
2.45	13.0	28.2	24 923 (81 768)	72.8 (1.52)
2.26	10.2	21.5	24 340 (79 857)	75.6 (1.58)
2.06	9.0	16.2	23 444 (76 917)	83.3 (1.74)
1.86	9.8	11.3	22 224 (72 914)	89.5 (1.87)
1.66	9.8	6.9	21 111 (69 263)	90.0 (1.88)
1.46	6.3	3.7	19 973 (65 527)	98.6 (2.06)
1.36	5.3	2.7	19 076 (62 584)	101.9 (2.13)
1.26	6.2	1.8	18 005 (59 073)	98.6 (2.06)

[a]Dotted reference line indicates commencement of terminal area energy management.

TABLE F-III.- SEVERAL NOISE EXPOSURE CRITERIA

"A" weighted sound pressure level, dB(A)	EPA permitted duration to accumulate daily exposure allowance[a]	Permitted industrial exposure limits by OSHA[b]	Kryter's criteria for zero hearing impairment for normal speech[c]
70	24 hr	No restriction	8 hr
75	7.6 hr	No restriction	4.7 hr
80	2.4 hr	No restriction	2.5 hr
85	46 min	No restriction	90 min
90	14 min	480 min	50 min
95	4.6 min	240 min	28 min
100	1.4 min	120 min	15 min
105	27 sec	3600 sec	540 sec
110	8.6 sec	1800 sec	354 sec
115	2.7 sec	900 sec	168 sec
120	.9 sec	(No criteria)	96 sec

[a]Assuming no contribution from the "quiet" period.

[b]Reference F-1.

[c]Reference F-2.

TABLE F-IV.- OCTAVE BAND SOUND PRESSURE LEVELS

[Far field acoustical specification, decibels (97.7 percent confidence level)]

Frequency, Hz	Sound pressure levels, dB, at distances from mobile launcher platform of -								
	45.7 m (150 ft)	82.3 m (270 ft)	149.3 m (490 ft)	259.1 m (850 ft)	457.2 m (1500 ft)	823.0 m (2700 ft)	1463.0 m (4800 ft)	2560.3 m (8400 ft)	4724.4 m (15 500 ft)
2	156.1	155.5	146.5	140.1	136.2	131.7	126.8	121.7	114.0
4	157.8	157.4	150.5	146.6	142.6	136.2	131.9	127.4	120.9
8	158.4	157.5	151.8	148.9	144.8	137.7	133.5	129.3	123.0
10	157.9	156.2	151.2	148.8	144.5	137.6	134.4	129.4	121.9
31.9	157.9	154.0	149.4	146.7	142.3	136.0	131.7	126.6	119.5
63	159.0	153.2	147.5	144.3	139.3	133.7	128.7	124.8	117.0
129	159.7	153.0	145.9	140.9	136.2	131.5	126.6	122.2	114.4
290	158.7	151.7	144.4	138.3	134.0	129.5	124.4	118.9	111.4
900	156.3	149.3	141.7	135.2	131.1	126.3	121.5	115.4	107.5
1000	153.0	146.9	139.2	132.5	128.8	125.2	119.5	113.3	104.2
2000	152.2	144.6	136.9	130.7	126.8	122.9	117.1	110.6	101.3
4000	150.2	142.2	134.6	129.4	124.8	120.1	114.0	108.4	98.8
5000	147.7	139.5	132.4	126.5	122.4	118.5	112.3	105.3	96.1
OASPL[a]	168.08	164.68	158.34	154.91	150.63	144.32	139.88	135.45	128.41

[a]OASPL is overall sound pressure level.

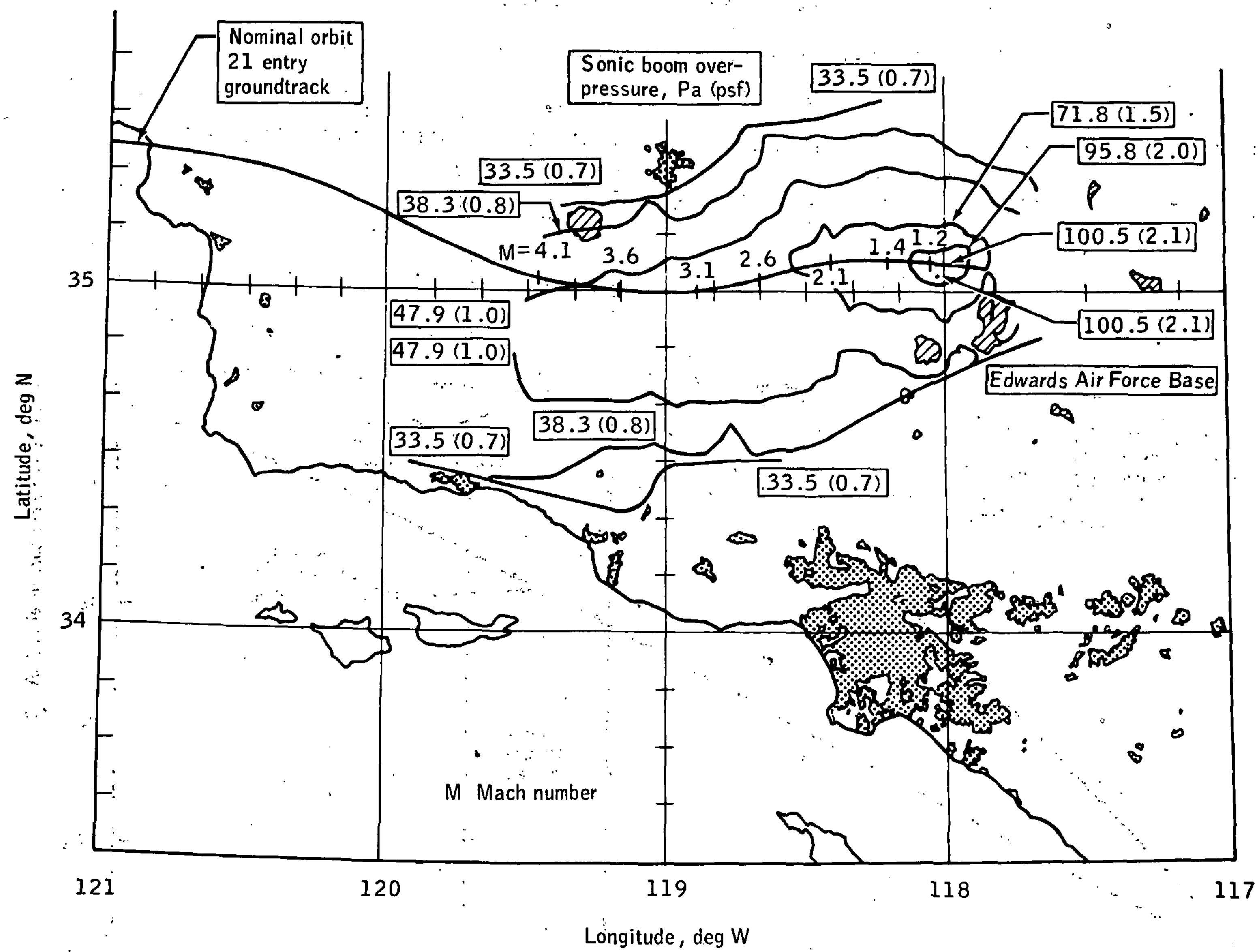


Figure F-1.- End of mission entry ground track (nominal orbit 21). Sonic boom overpressure isobars are given in N/m^2 (lb/ft^2).

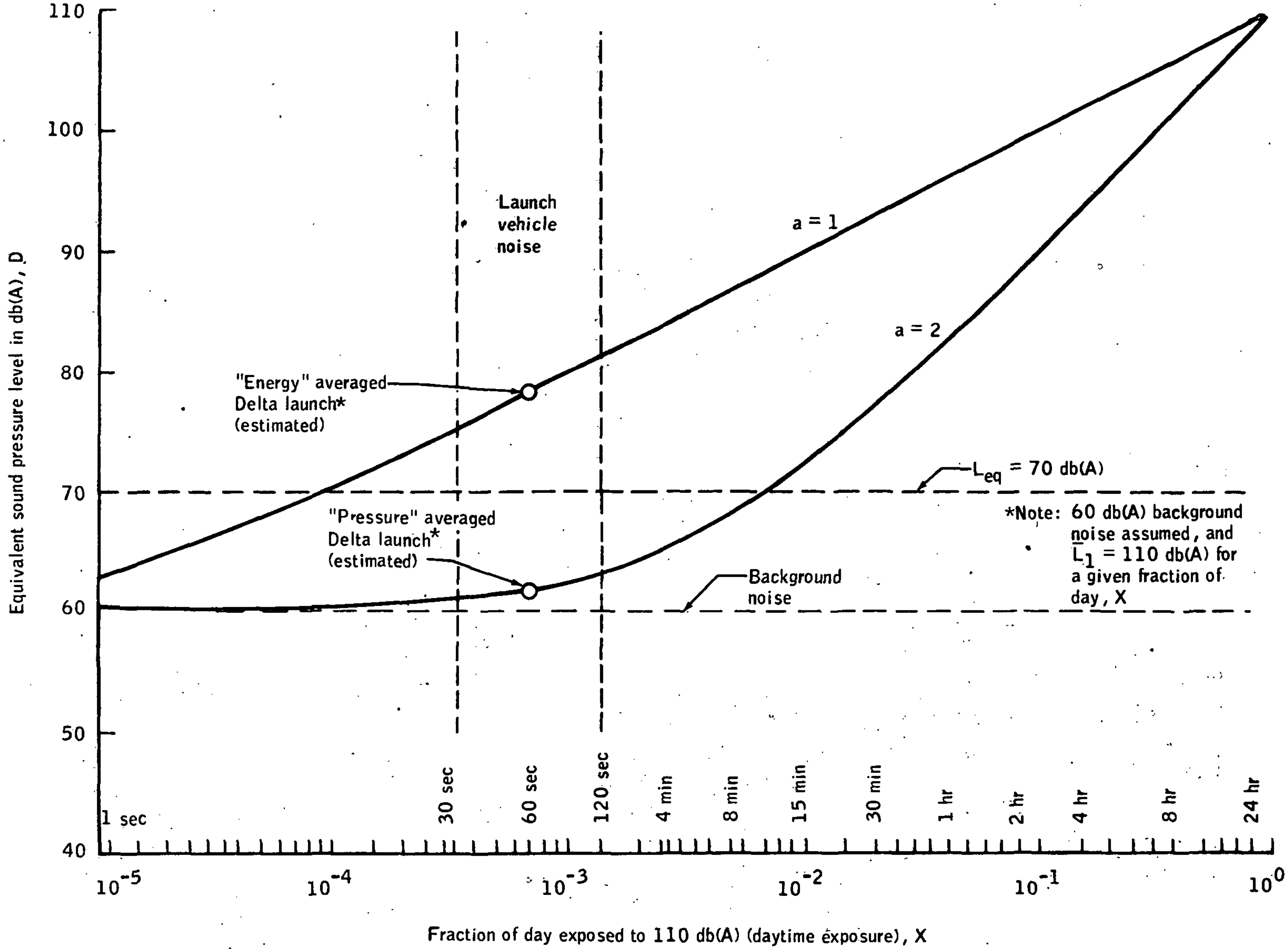
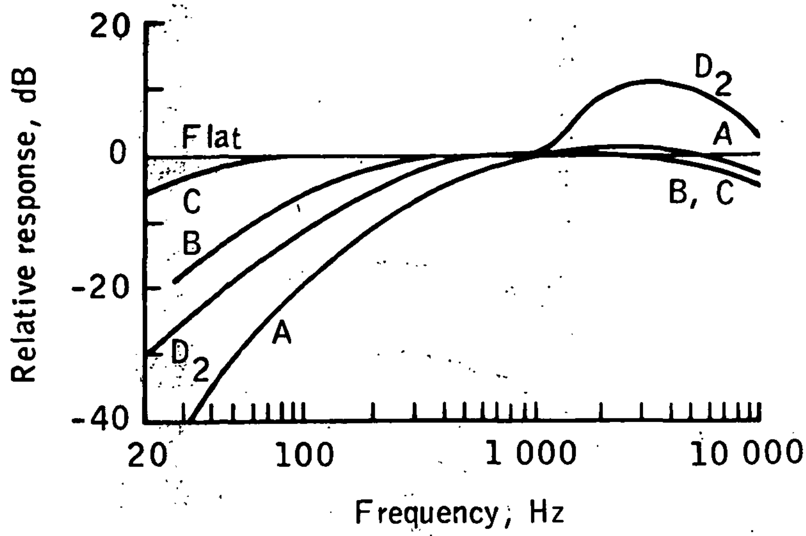
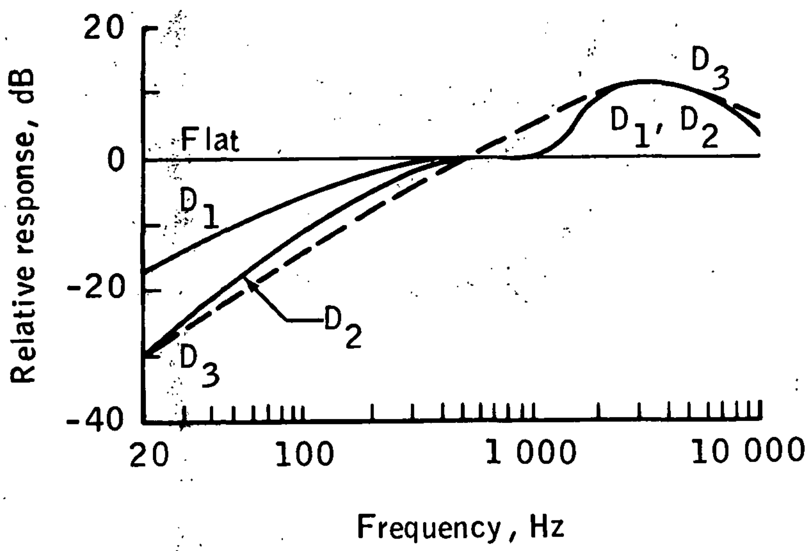


Figure F-2.- Plot of sound-averaged energy contrasted with plot of sound-averaged pressure.



(a) Standard weightings A, B, and C (25), and (newly proposed and herein recommended) D (462).



(b) Recently proposed D_1 (458), D_2 (same as in part "a"), and D_3 (898) weightings; D_3 is adjusted upward by 6 decibels in this figure to better show relation to D_2. In the text, unless otherwise specified, "D" weighting will refer to D_2.

Figure F-3.- Frequency weightings for sound level meters. Because a significant portion of the launch vehicle noise is below 1000 hertz, the use of D and A scales are especially appropriate when considering the effects of launch vehicle noise on man. The A scale is much more favorable to the launch vehicle situation than is the $D(D_2)$ scale.

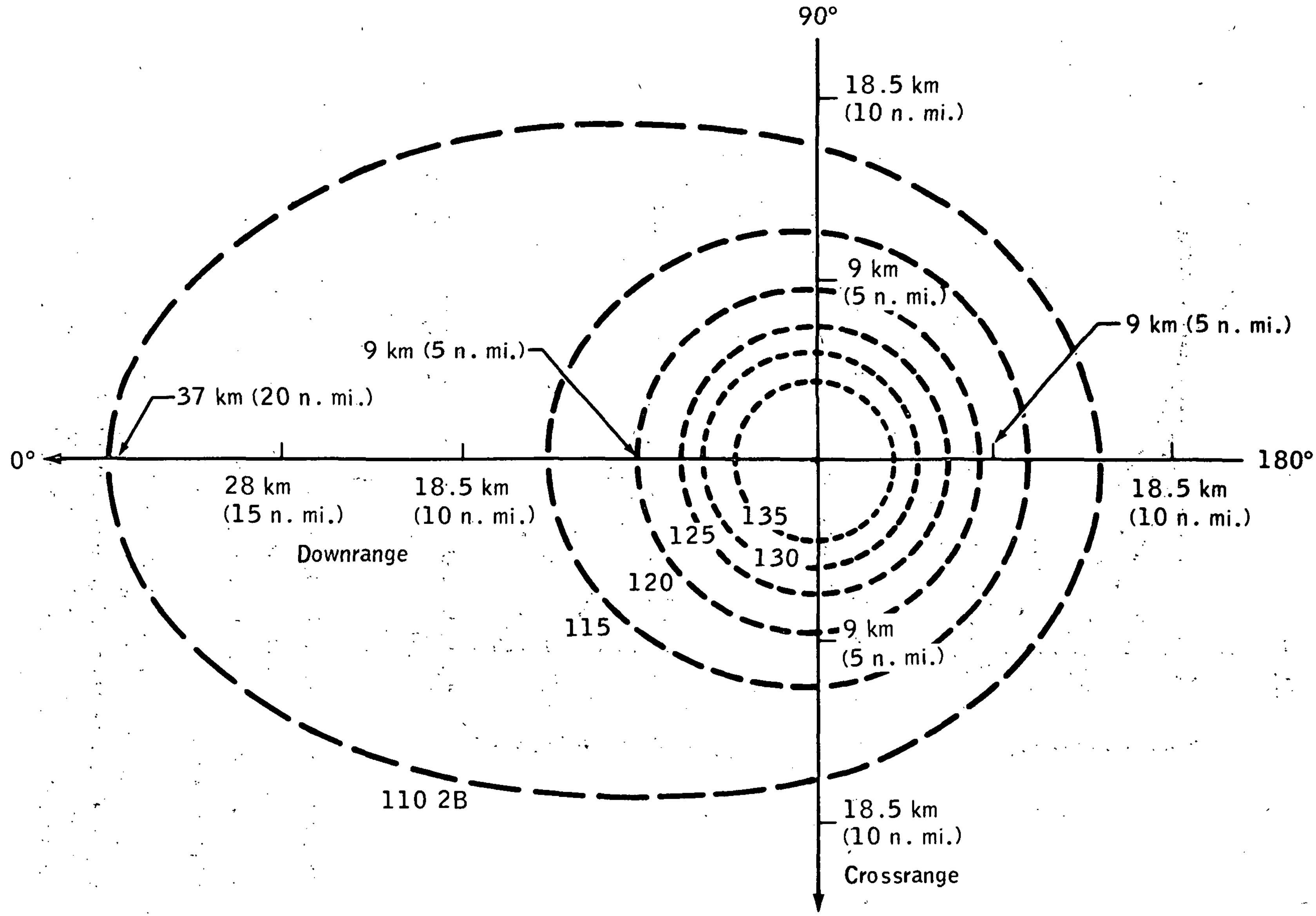


Figure F-4.- Ground plane maximum overall sound-pressure-level contours for Shuttle launch with 2.9×10^7 newtons (6.6×10^6 pounds) thrust.

APPENDIX G - MEDICAL AND BIOLOGICAL ALLOWABLES

This appendix consists of material from three sources:

1. "Hydrogen Chloride Exposure Criteria (Humans)," a report of work in progress at the NASA Langley Research Center (LaRC). The report was submitted to the workshop by G. L. Gregory of LaRC.

2. "Medical/Biological Consequences - 'Real Case' Effects," excerpts of a workshop presentation by G. L. Gregory of LaRC.

3. "Pollutant Standards," contains two tables presented by NASA John F. Kennedy Space Center (KSC) staff members. The tables summarize standards and proposed standards of allowable pollution that might affect the Shuttle Program. H. W. Rudolph (of KSC) presented his table of chemical standards. A noise standards table from the Occupational Safety and Health Administration was also presented.

HYDROGEN CHLORIDE EXPOSURE CRITERIA (HUMANS)

The 1972 Environmental Statement references three hydrogen chloride HCl exposure criteria for humans:

1. An occupational emergency exposure limit of 30 p/m for 10 minutes

2. A short-term public exposure limit of 4 p/m for 10 minutes

3. A long-term public exposure limit of 2 p/m for 60 minutes

The 1972 Environmental Statement discussion of Shuttle HCl emissions and their impact on ambient air quality is based on the assumption that these criteria are the "safe" levels and that NASA's predictions of ambient HCl concentrations are below these "safe" levels. It is properly noted in the Environmental Statement that an EPA air quality standard for HCl does not exist.

After approximately 3 years of field monitoring experience in the detection of HCl concentrations in ambient air, debriefings of field personnel after a launch have resulted in the following observations or comments:[1]

1. Threshold of odor detection of HCl is approximately 0.05 p/m.

2. Instantaneous exposure of personnel to an HCl concentration of 0.05 p/m is quite noticeable (odor) and disagreeable.

---

[1]These observations agree with U.S.S.R. data (refs. G-1 to G-3).

3. Instantaneous exposure of personnel to an HCl concentration of 1 or 2 p/m results in eye and skin irritation (short term, during exposure).

In addition, field monitoring programs of HCl from other sources have resulted in similar observations. For example, in October 1974, NASA participated in an Environmental Protection Agency program to monitor HCl downwind from an incinerator ship in the Gulf of Mexico (ref. G-4).

The incineration process was the high-temperature combustion of chlorinated hydrocarbon waste products (20 000 kg/hr) with resultant combustion products of HCl, CO, and H_2O (hydrogen chloride, carbon monoxide, and water). During this monitoring program, sampling and crew personnel aboard the research vessel, located downwind of the incinerator ship, were exposed to a maximum of approximately 7 p/m HCl. During this 2.5-minute exposure, when HCl concentrations approached 5 p/m, instrument operators and above-deck ship personnel experienced eye and skin irritation as well as breathing difficulty. The ship's captain was preparing to abort the sampling pass when contact with the exhaust plume was terminated. At concentrations of approximately 0.05 p/m, a distinct odor was detected similar to that experienced during launch vehicle effluent monitorings and solid rocket motor (SRM) static test firings.

The current exposure guidelines suggested by the National Research Council-National Academy of Sciences Committee on Toxicology (NRC[2]) are still the same as those quoted in the 1972 Environmental Statement.
These criteria are:

1. Short-term public limits (STPL)

    a. 4 p/m for 10 minutes (8 p/m peak)
    b. 2 p/m for 30 minutes
    c. 2 p/m for 60 minutes
    d. 2 p/m for 1 hr/day
    e. 0.7 p/m for 5 hr/day; 3-4 days/month

2. Occupational emergency exposure limits (EEL)

    a. 30 p/m for 10 minutes
    b. 20 p/m for 30 minutes
    c. 10 p/m for 60 minutes

3. Public emergency limits (PEL)

    a. 7 p/m for 10 minutes (14 p/m peak)
    b. 3 p/m for 30 minutes
    c. 3 p/m for 60 minutes

---

[2]April 8, 1975, memorandum from Ralph C. Wands, Director, Advisory Center on Toxicology, National Research Council, National Academy of Sciences, to J. Briscoe Stephens, NASA George C. Marshall Space Flight Center (MSFC).

There is some question as to why the field observations suggest lower exposure criteria than the NRC values. The difference might be explained in part by the fact that the current exposure criteria refer to levels which produce medically measurable effects. Levels at which subjective annoyance or temporary irritation occurs must necessarily be lower. Another source of difference might be in the phase state of HCl. As best determined, the NRC exposure criteria are for gaseous HCl concentration. During the field studies, the HCl irritant may be a combination of acid aerosol HCl and gaseous HCl that may be more irritating than pure HCl gas. However, based on both field and laboratory data to date, the majority of HCl deposited downwind (5 kilometers or more) from a Shuttle launch (and those irritation situations discussed earlier) is believed to be gaseous HCl. Possibly the presence of a small amount of aerosol HCl in combination with gaseous HCl poses a more severe irritant mixture. The U.S.S.R. literature (refs. G-1 to G-3) partially supports the aerosol idea in that they suggest the following exposure criteria for HCl aerosols:

Odor threshold: 0.04 to 0.08 p/m

Eye, respiratory threshold: 0.1 to 0.05 p/m of irritation

Certainly the U.S.S.R. values appear to more closely correlate with field observations during the LVE program. (Only abstracts of the referenced U.S.S.R. reports are available.)

Another possible answer to the HCl exposure question is that maybe some other species in the SRM cloud is the irritant being noticed in the field; Cl_2 or ClO^- compounds being possible choices. Further toxicological studies are desirable.

MEDICAL/BIOLOGICAL CONSEQUENCES - "REAL CASE" EFFECTS

Field observations of HCl indicate an odor threshold of 0.05 p/m; objectionable eye and skin irritation at 1 p/m; and major difficulty in breathing, eye irritation, and skin irritation at 7 p/m. Consideration of these data suggests that the present standards may be high, even though safe. It may be desirable to establish annoyance levels. Also, further investigation of the apparent discrepancy between established HCl standards and field observations may be most fruitful in researching the phase of HCl and the possible effects of other effluents.

Field observations of aluminum oxide (Al_2O_3) effluents indicate that particle fallout may be an annoyance and that acidic particles or aerosols reach ground level at considerable distances from the launch site. Conclusions drawn from this indication are that evaluations should be made of the annoyance factor and the acidic particle problem.

POLLUTANT STANDARDS

A number of effluent exposure standards exist or have been proposed that would affect the Florida Space Shuttle launch site. Some of these standards are summarized in table G-I. Occupational Safety and Health Administration noise exposure limits (ref. G-11) are shown in table G-II.

REFERENCES

G-1. Data for the Hygienic Evaluation of Hydrochloric Acid Aerosol (Hydrochloride Gas) as an Atmospheric Pollutant. In: Limits of Allowable Concentrations of Atmospheric Pollutants, Book 6; U.S.S.R. Literature on Air Pollution and Related Occupational Disease, vol. 9, pp. 18-28, 1962.

G-2. The Problem of Combined Action of Three Mineral Acids. In: Biological Effect and Hygienic Significance of Atmospheric Pollutants, Book 1/9, V. A. Ryazanov and M. S. Gol'dberg, eds. (Translated from Russian by B. S. Levine), U.S.S.R. Literature on Air Pollution and Related Occupational Diseases, vol. 16, pp. 76-81, 1968.

G-3. Hygienic Determination of Limits of Allowable Concentrations of Chlorine and Hydrochloride Gases Simultaneously Present in Atmospheric Air. In: Limits of Allowable Concentrations of Atmospheric Pollutants, Book 6; U.S.S.R. Literature on Air Pollution and Related Occupational Diseases, vol. 9, pp. 55-61, 1962.

G-4. Wastler, T. A.; Offutt, Carolyn K.; Fitzsimmons, Charles K.; and Des Rosiers, Paul E.: Maritime Administration Chemical Waste Incinerator Ship Project. Disposal of Organochlorine Wastes by Incineration at Sea, vol. 2, appendix 4, EPA-430/9-75-014, July 1975.

G-5. Occupational Safety and Health Administration: Air Contaminants. Code of Federal Regulations, title 29, part 1910.1000, July 1, 1976.

G-6. Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment with Intended Changes for 1976. American Conference of Governmental Industrial Hygienists, Oct. 1976.

G-7 Committee on Toxicology: Chlorine and Hydrogen Chloride. National Academy of Science, National Research Council, 1975.

G-8. Environmental Protection Agency: Clean Air Amendments of 1970, PL-604. Approved Dec. 31, 1970.

G-9. Department of Pollution Control: Rules of the State of Florida, Supplement no. 57, chapter 17-2. (Department of Pollution Control now superseded by Department of Environmental Regulation.)

G-10. Environmental Protection Agency: National Primary Ambient Air Quality Standards for Particulate Matter. Code of Federal Regulations, title 40, part 50.6, July 1, 1976.

G-11. Occupational Safety and Health Administration: Occupational Noise Exposure. Code of Federal Regulations, title 29, part 1910.95, July 1, 1976.

TABLE G-I.- EXPOSURE STANDARD FOR PROPELLANT EFFLUENTS

Type of standard	Effluent species			Source
	HCl (a)	Al_2O_3	CO	
Threshold limit value (time weighted average)	5 p/m ceiling value	10 mg/m^3	50 p/m	Reference G-5
			15 p/m	References G-6 and G-7
Maximum allowable concentration for workers	5 p/m			Reference G-6
Public air quality standards	(1 p/m hr^{-1}) (0.2 p/m (recurrently)) (0.01 p/m (continuous))		9 p/m/8-hr/yr 35 p/m for 1 hr/yr	Reference G-8 Reference G-9
Public particulate limit		75 mg/m^3 annual geometric mean 260 mg/m^3 maximum 24-hr concentration during year		Reference G-10
		60 mg/m^3 annual geometric mean 150 mg/m^3 maximum 24-hr concentration during year		Reference G-9

[a]Values in parentheses are KSC recommended values for Space Shuttle.

TABLE G-II.- OCCUPATIONAL SAFETY AND HEALTH PERMISSIBLE NOISE EXPOSURES[a]

[Impact or impulsive noise not to exceed peak sound pressure level of 140 dB]

Permissible duration per day, hr	Slow response sound level on "A" scale, dBA
8	90
6	92
4	95
3	97
2	100
1.5	102
1	106
.5	110
.25	115

[a]For two or more noise sources,

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} \ldots \frac{C_n}{T_n} \leq 1$$

where C_n indicates the total time of exposure at a specific noise level and T_n indicates the total time of exposure permitted at that level.

APPENDIX H - LAUNCH CLOUD NEUTRALIZATION FEASIBILITY STUDY

This appendix consists of two items that were submitted to the workshop by the NASA Langley Research Center (LaRC) staff.

1. "Ground Cloud Neutralization" by the LaRC staff

2. "Feasibility Study of Launch Vehicle Ground Cloud Neutralization," excerpts of a paper by P. C. Vander Arend, S. T. Stoy, and T. E. Kranyecz of Cryogenic Consultants, Inc.

GROUND CLOUD NEUTRALIZATION

The research program undertaken to examine and demonstrate the effectiveness of chemical agents and delivery systems in neutralizing the hydrogen chloride (HCl) emitted by solid propellant motors (SRM) in the troposphere has made good progress. Several basic approaches to introducing the neutralization agent(s) at ground level into the exhaust ground cloud have been identified in a study contract. This study shows clearly that the delivery of neutralizing agent into the ground cloud should be carried out during the formation of the cloud and with equipment located on the ground. Delivery rates need to be such that all the required neutralizing agent is injected in 10 seconds.

Because of short delivery time, a concentrated solution of sodium carbonate (Na_2CO_3) should be used as the neutralizing agent for the ground cloud. The advantages of this solution are

1. Low pressure, safe storage for indefinite periods of time

2. Nontoxic vapors

3. Cost of solution per launch is reasonable

4. Lowest cost nontoxic ground-installed delivery system

The delivery of neutralizing agent to the column cloud needs to be carried out by aircraft as soon as possible after the launch. The preferred aircraft is the Sikorsky CH-54B helicopter that can pick up a tank and carry it external to its fuselage. The only feasible neutralizing agent to be used for delivery by aircraft is ammonia (NH_3). The ammonia will be stored in the tank at high pressure and at ambient temperature, and it will be discharged from the tank without need for an external pressurization system. The dispersion of ammonia in the column cloud will be reasonably effective, because, when the liquid expands to atmospheric pressure, it will separate into a fog. This fog will contain approximately 72-percent liquid and 28-percent vapor. The liquid will exist as very small particles. Differences in density between the ammonia cloud and the column cloud will provide relative motion. As a result, a single pass through the cloud by a helicopter flying at a low speed of 60 to 80 km/hr will cover a large column of the cloud.

The Delta launches appear to be suited for a program of injecting the neutralizing agent into the ground cloud. Scale of the test equipment will be approximately one-thirtieth of that for the Space Shuttle. The tank is quite small, and it should be possible to move the tank about for variation of the injection point into the ground cloud.

It is essential that the hypothesis of two separate (ground and column) clouds be verified. This could be done by injecting a tracer in the ground cloud during its formation and analyzing the cloud(s) for a period of 30 minutes to 1 hour after launch. The analysis of the contents of the cloud should preferably be carried out with a slow-speed aircraft. This would make it possible to "map" the cloud more closely. It appears useful to provide a correlation between the cloud volume and concentration of HCl as a function of time. This is particularly true for a column cloud because this cloud can only be neutralized by airborne equipment.

FEASIBILITY STUDY OF LAUNCH VEHICLE GROUND CLOUD NEUTRALIZATION (EXCERPTS)

During the launch of a Space Shuttle, large quantities of HCl are released by the vehicle and contained in the exhaust cloud. The 1972 Environmental Statement for the Space Shuttle Program states that operational constraints will be imposed on Space Shuttle launches to eliminate the possibility of unacceptable HCl concentrations in the troposphere. In addition to the concern over the possible effects of relatively large, localized, low-level releases of HCl, there is a possibility of rain removing HCl from exhaust clouds in concentrations sufficient to have an adverse effect on the surrounding environment during normal launches. The Space Shuttle will, therefore, require that certain precautions be taken to defer launches if weather conditions are such that the exhaust cloud concentrations, movements, and weather indicate unacceptable conditions that might affect the surrounding environment.

The Space Shuttle traffic model involves a high number of launches per year with quick turnaround on each flight; therefore, careful consideration must be given to the impact of launch constraints on Shuttle operations. The possibility of delaying launches because of possible unacceptable environmental impact of HCl would be cause for concern.

The introduction of chemical agents into the cloud formed by the Space Shuttle at the time of launch holds out the possibility that the contained HCl may be neutralized and rendered harmless to the immediate environment.

Background

The solid rocket engines of the booster of the Space Shuttle deliver as much as 50 000 kilograms of HCl to the troposphere during the first 20 seconds of burning. With the existence of inversion layers at an altitude of 2 to 3 kilometers, the exhaust cloud with contained HCl may drift over surrounding territory of the NASA John F. Kennedy Space Center. In case of rain, the HCl may be washed out and be delivered to the ground in the form of an acid solution.

A relatively large number of chemical agents capable of neutralizing the HCl are available as bulk commmercial products. These agents may be delivered as a solid, liquid solution, or gas to the cloud formed during the initial 20 seconds of engine burn. The distribution of HCl in the cloud has been analyzed as a function of launch pad geometry and rate of rise of the vehicle during the first 20 seconds of burn.

Delivery systems of various types have been developed to bring the chemical agent in close contact with the HCl. Approximately one-third of the neutralizing agent can be delivered from a ground-installed system at the launch pad; two-thirds of it appears to need delivery by aircraft. Only one chemical agent (NH_3) may be reasonably considered for delivery by aircraft, because weight and bulk of all other agents is too large. Mixing of the neutralizing agent with the contents of the cloud is caused by the extreme turbulence present in the cloud shortly after its formation.

A conceptual design of ground-installed and airborne delivery systems has been developed. The design lends itself to testing of the concept on a small scale. A cost analysis of these systems has also been made.

Modeling

Before fully implementing the system for the Space Shuttle Program, modeling at a reduced scale should be performed. Previous discussion (not included in this appendix) indicates that Delta rocket launches appear to be suited for such a modeling program. The ground-based equipment is small, is shop fabricated, and can be moved about the Delta launch facility without great difficulty.

An airborne delivery system for injection of NH_3 into the column cloud can be carried by almost any helicopter. The total amount of NH_3 to be carried is on the order of 600 kilograms. Total weight of tank, nozzles, liquid, and other parts of the system will be on the order of 1000 kilograms.

Sampling and Data Correlation

It is essential that the hypothesis fo two separate clouds be verified. This could be done by injecting a tracer into the ground cloud during its formation and, then, analyzing the cloud(s) for a period of 30 minutes to 1 hour after launch. The analysis of the cloud contents should be carried out with a slow-speed aircraft. This would make it possible to "map" the cloud more closely.

Providing a correlation between the cloud volume and concentration of HCl as a function of time appears useful. This is particularly true for the column cloud because this cloud can only be neutralized by airborne equipment.

Correlating between weather conditions during the launch and the formation and final shape of the cloud appears useful. Wind velocity and direction as a function of altitude is expected to greatly influence the size of the final cloud and its HCl concentration measured in parts per million. Plots of this type of data will be quite useful in predicting the potential effects of washout on the surrounding territory.

Recommendations

The study shows clearly that the delivery of a neutralizing agent into the ground cloud should be carried out during the formation of the cloud and with equipment located on the ground. Delivery rates need to be such that all the required neutralizing agent is injected in a period of 10 seconds.

To make equipment reasonably small, tanks containing the neutralizing agent should be located in the area over which the exhaust gases from the rocket flow. Then, pipe sizes of the delivery system will be small; startup of flow of solution is rapid; and cutoff, in case of launch abort, can be reasonably achieved.

Because of short delivery time, a concentrated solution of Na_2CO_3 should be used as the neutralizing agent. The advantages of this solution are

1. Low pressure, safe storage for indefinite periods of time

2. Nontoxic vapors

3. Cost of solution per launch is reasonable

4. Lowest cost nontoxic ground-installed delivery system

The delivery of neutralizing agent to the column cloud needs to be carried out by aircraft as soon as possible after the launch. The preferred aircraft is the Sikorsky CH-54B helicopter that can pick up a tank and carry it external to its fuselage. The only feasible neutralizing agent to be used for delivery by aircraft is NH_3. The NH_3 will be stored in the tank at high pressure and ambient temperature and will be discharged from the tank without need for an external pressurization system. The dispersion of NH_3 in the column cloud will be reasonably good because the liquid expanded to atmospheric pressure will separate into a fog. This fog will contain approximately 72-percent liquid and 28-percent vapor. The liquid will exist as very small particles. The difference in density between the NH_3 cloud and the column cloud will provide relative motion. As a result, a single pass through the cloud by a helicopter flying at a low speed of 60 to 80 km/hr will cover a large volume of the cloud.